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Energy Efficiency and Greenhouse Gas Emissions in Digestate Utilization

Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Technology

Department of Energy Technology,
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Abstract of Master's Thesis

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Abstract

Biogas production is an emerging energy technology, which serves also as a waste treatment and reduction method. As the biogas production process is optimized in terms of waste management and economy, also the residue of anaerobic digestion, digestate, should have a useful purpose. Due to notable nutrient content, digestate is often considered as a potential fertilizer.

The object of this Thesis is to determine energy efficiencies and GHG emissions in different application chains of digestate, which are usable in Finland. The results benefit economic and environmental feasibility studies on both digestate treatment and whole biogas process. As a secondary object, an excel-tool was developed for efficient data processing, which may also be used for further studies of more specific boundaries. Prior to the main calculations, biogas, anaerobic digestion and digestate are discussed in basics, providing the background information for digestate applications. Four application chains, soli improver-growing media, solid fuel (fertilizer pellet), ammonium sulphate fertilizer and liquid fertilizer, are chosen for the energy and emission calculations.

The energy and emissions data are first provided for separate processes and applications. Next, the data are unified into chains and, finally, the energy and GHG balances of each application chain are calculated, discussed and compared together. The greatest energy demands are found to occur in two main processes, thermal drying and ammonia stripping, while savings are generated by energy content of solid fuel and synthetic fertilizer substitution by nutrient content. As for GHG emissions, the highest credits are gained by avoidance of N-fertilizer production.

Based on both the energy efficiency and GHG emissions, the solid fraction of digestate should be applied as soil improver-growing media and the liquid as fertilizer directly after screw press separation. This method could result in primary energy saving of 30 to 40 kWh and GHG saving of more than 50 kg CO_2 equivalent per tonne raw digestate treated. The highest energy demand and GHG emissions are generated by the fertilizer pellet. Nonetheless, significant uncertainty is involved in the results due to dependency on variable properties of digestate and lack of energy and emission data on the processes and applications. Thus, the main object, provision of data for further feasibility studies, was not reached perfectly.

Keywords digestate, energy efficiency, primary energy, greenhouse gas, biogas

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Tiivistelmä

Biokaasun tuotanto on kehittyvä ja kasvava energiantuotantomuoto, joka toimii lisäksi jätteenkäsittelyprosessina. Kun biokaasuprosessi, jossa orgaanisen aineen mädättäminen synnyttää biokaasua, optimoidaan, myös mädätysjäännökselle pyritään löytämään käyttökohde. Huomattavan ravinnesisällön vuoksi lannoitus on jäännöksen yleisin käyttösovellus. Tämän diplomityön tavoite on määrittää mädätysjäännöksen hyödyntämisen energiatehokkuus ja kasvihuonekaasupäästöt eri prosessointi- ja käyttövaihtoehdoissa, jotka ovat sovellettavissa suomalaiseen toimintaympäristöön. Tulokset tukevat sekä mädätysjäännöksen käsittelyn että koko biokaasuprosessin talous- ja ympäristöarviointeja. Toinen työn tavoite on tiedonkäsittelyä tehostavan excel-työkalun kehittäminen.

Biokaasun, mädätyksen ja mädätysjäännöksen perusteet, joiden pohjalta tarkasteltavat käyttövaihtoehdot valitaan, käsitellään työn alussa. Neljä laskennassa arvioitavaa käyttökohdetta ovat maanparannusaine-kasvualusta, kiinteä polttoaine (lannoitepelletti), ammoniumsulfaattilannoite ja nestemäinen lannoite. Energia- ja päästötiedot kerätään ensin erillisille prosesseille, jonka jälkeen ne yhdistetään lopputuotteiden käyttöön johtaviksi ketjuiksi. Lopuksi eri tuotanto- ja käyttöketjujen energiatehokkuudet ja kasvihuonekaasupäästöt lasketaan, arvioidaan erikseen sekä verrataan keskenään. Prosessoinnissa eniten energiaa kuluu termisessä kuivauksessa ja ammoniakin strippauksessa, kun taas kiinteän polttoaineen energiasisältö ja lannoitekäytössä synteettisten lannoitusaineiden korvaus tuottavat suurimmat energiansäästöt. Puolestaan synteettisen typpilannoitteen tuotannon välttäminen säästää eniten kasvihuonekaasupäästöjä.

Sekä energiatehokkuuden että päästöjen perusteella mädätysjäännös tulee erottaa ruuvipuristimella, jonka jälkeen kiinteä jae hyödynnetään maanparannusaine-kasvualustana ja nestejae suoraan nestemäisenä lannoitteena. Toimintamalli tuottaa 30 – 40 kWh primäärienergiasäästöt ja yli 50 kg CO_2-ekvivalentin kasvihuonekaasusäästön käsittelemätöntä mädätysjäännöstonnia kohden. Lannoitepelletin prosessointi- ja käyttöketju tuottaa sekä suurimman energiankulutuksen että kasvihuonekaasupäästön. Tuloksiin liittyy kuitenkin huomattavaa epävarmuutta, sillä ne riippuvat keskeisesti jäännöksen ominaisuuksista ja koska jäännöksen prosessoinnista on saatavilla vähän tietoa. Siten työn päätavoite, eli taustatiedon määrittäminen myöhempiin käytettävyysanalyyseihin, ei toteutunut täydellisesti.

Avainsanat mädätysjäännös, energiatehokkuus, primäärienergia, kasvihuonekaasu, biokaasu

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This Thesis was my last project before graduation as a Master of Science from Aalto University, which I carried out during the spring 2014 for Gasum Oy in Espoo. I am grateful for the support provided by the personnel at Gasum, especially my advisor M.Sc. Olli Nevalainen as well as M.Sc. Tuomas Niskanen, who accompanied me in the same office room for the whole period. From Aalto University, I sincerely thank my supervisor Professor Mika Järvinen for being flexible and attentive to my work.

However, I dedicate my greatest and most humble word of thanks to my family: my mother, Aila, my brother, Eetu, and my girlfriend, Salla. I have enjoyed my life and made the right choices with their support. I would have never ended up in the Helsinki University of Technology without my mother and brother showing example of courage. The university, the student organizations and my fellow students, especially the BOTs, have made my years in Otaniemi irreplaceable: I cannot imagine a better place to study and live one's youth. Last but not least, I was not the relatively positive person I am without Salla, who bears me on the bad days and makes the sunny ones even brighter.

During this spring, I have been preparing to face a great barrier in my life as I have to move forward and leave the student life behind. The Thesis has been a proper final boss for my studies since I do not have that academic personality after all. However, I feel pride and gratitude for the job done and will continue with enthusiasm and drive towards new challenges.

Espoo, 27th May 2014

Aleksi Haverinen

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List of Symbols

A	*ash content*	*%*
E	*primary energy content*	*kWh kg^{-3}*
η	*efficiency*	*%*
ΔG_f	*Gibbs free energy*	*kJ mol^{-1}*
d	*density*	*kg nm^{-3}*
M	*moisture content*	*%*
q	*heating value*	*MJ kg^{-1} or kWh nm^{-3}*
W	*Wobbe Index*	*kWh nm^{-3}*

List of Abbreviations

ABPR	*Animal by-product regulation*
AD	*Anaerobic digestion*
BAT	*Best available technology*
BREF	*BAT reference document*
CEN	*European Committee for Standardization*
CHP	*Combined heat and power production*
CNG	*Compressed natural gas*
CO_2-eq	*Carbon dioxide equivalent*
COD	*Chemical oxygen demand*
DM	*Dry matter*
EEA	*European Environment Agency*
EU	*The European Union*
GHG	*Greenhouse gas*
GWF	*Global warming factor*
GWP	*Global warming potential*
HRT	*Hydraulic retention time*
HHV	*Higher heating value*
IEA	*International Energy Agency*
IED	*Industrial emission directive*
IPCC	*Intergovernmental Panel on Climate Change*
LCA	*Life cycle assessment*
MSW	*Municipal solid waste*
ODM	*Organic dry matter*
PED	*Primary energy demand*
PEF	*Primary energy factor*
RCP	*Representative concentration pathway*
RP	*Reference path*
SEF	*Specific emission fraction*
SIGM	*Soil improver-growing medium*
SP	*Special option of screw press use*
TSE	*Transmissible spongiform encephalopathy*
WWTP	*Wastewater treatment plant*

1 INTRODUCTION

1.1 Background of biogas production

The climate change and the exhaustion of fossil fuel reserves challenge the global energy field to develop new energy production techniques in order to decrease *greenhouse gas (GHG)* emissions worldwide and, on the other hand, secure energy production on the 21st century. *The first part of the Fifth Assessment Report* by *Intergovernmental Panel on Climate Change (IPCC)* suggests that even though the trend of emissions produced world-wide could be turned downwards around year 2020, the global mean temperature would rise one degree and the global mean sea level 0.4 meters compared to reference period of 1986-2005, see Figure 1.1. (IPCC, 2013) Renewable energy sources are expected to gain increasing share of production as the environmental and economic pressure push towards climate friendly processes.

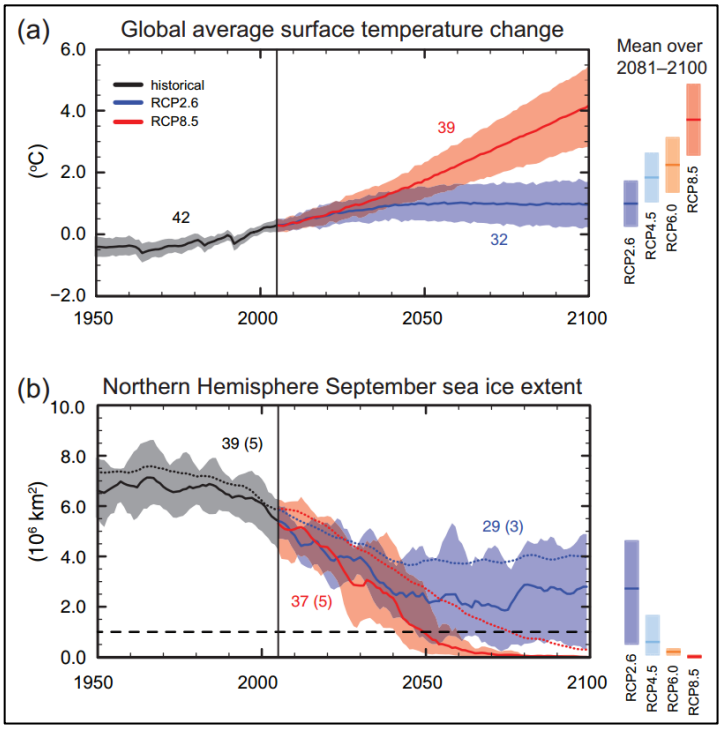

Figure 1.1 Global average surface temperature change (a) and northern hemisphere sea ice extent (b) forecasted in IPCC's four Representative Concentration Pathways (RCPs). Adapted from IPCC (2013).

One of the most potential renewable energy sources is biomass. Biomass is material that derives from a living or recently living biological source, such as plants, wood or organic household waste. Biomass can be used directly as a carbon neutral fuel or refined into a high energy content product, usually bio-oil or biogas. Different utilization processes are shown in Figure 1.2. (Deublein & Steinhauser, 2011) In Europe, biofuels also generate substantial economic benefits in e.g. employment since at the moment the continent is highly dependent on imported energy sources. (European Comission, 2006)

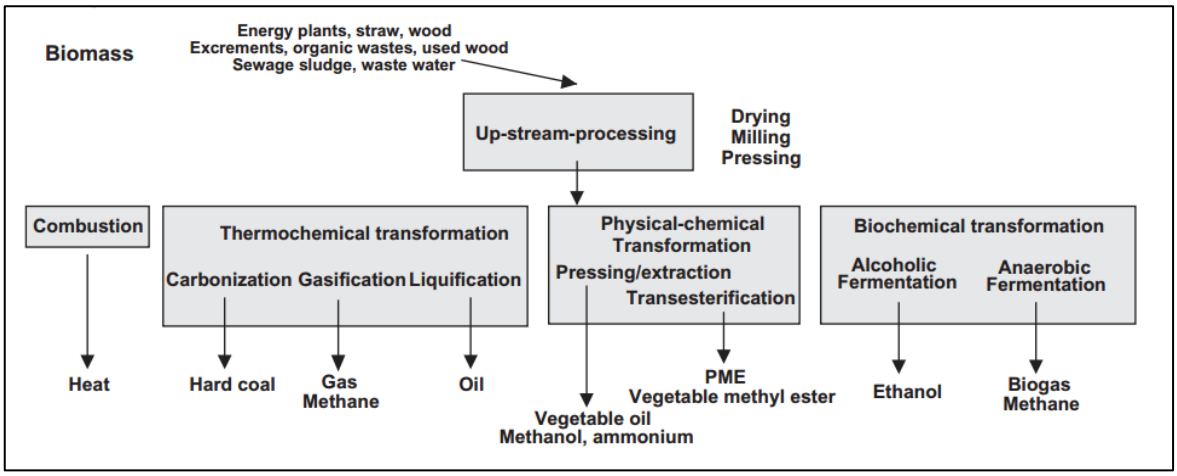

Figure 1.2 Process alternatives for energy production from biomass. Adapted from Deublein & Steinhauser (2011).

Biogas is a product of *anaerobic digestion (AD)* of organic matter. Biogas can be produced in a reactor from e.g. sewage sludge, manure or organic waste and can be used directly to electricity and heat production. By upgrading to biomethane, it can be utilized as a substitute for natural gas e.g. by injecting to a natural gas network. Since biogas is a carbon neutral energy source, its use for energy production instead of fossil fuels reduces GHG emissions. Heat production from biogas in Finland in 2012 was 408.8 GWh, power production was 159.6 GWh and the energy amount wasted in flare combustion of biogas was also significant: 114.5 GWh. The sum of heat and power production equals to 0.15% of total energy use while the overall biogas potential from wastes is estimated to be between 6.7 and 18 TWh (in 2015) per year (Asplund, et al., 2005). (Huttunen & Kuittinen, 2013)

Natural degradation processes occur constantly wherever the organic matter decomposes. In the absence of oxygen, anaerobically, these processes produce methane *(CH_4),* which is main component of biogas. In 100 year scope *Global Warming Potential (GWP_{100})* of methane is 25, which indicates that it is 25-fold stronger greenhouse gas than carbon dioxide (CO_2) (IPCC, 2007). The more organic matter, e.g. animal manure, is used to produce biogas, the more potential methane is turned into carbon dioxide in combustion and the less climate damage is caused (Clements, et al., 2012). Thus, use of biogas in energy production is not only carbon neutral choice but it also decreases strength of GHGs. The most notable methane producers of human activity are cattle farming, cultivation of rice, energy industry and waste disposal to landfills. Collection of landfill gas accounts for the majority of biogas production is Finland (Huttunen & Kuittinen, 2013) while the primary target is to gather organic waste, instead of landfills, to bioreactors for biogas production and controlled waste treatment and reduction (Ministry of the Environment, 2010). According to Deublein & Steinhauser (2011) anaerobic processing reduces quantity of biomass substantially more than aerobic processing (i.e. composting). (IPCC, 2007) To sum up, the main benefits gained from biogas production are (Al Seadi, et al., 2008):

- Renewable, carbon neutral and local energy source
- Reduction in quantity of waste in AD
- Decreasing strength of GHGs
- Valuable digestate to substitute e.g. synthetic fertilizers

Anaerobic digestion is said to be used already in Assyria in the Ancient Dark Age for heating bath water while reliable evidences indicate use in 1895 to fuel streetlamps in Exeter, England (Stamatelatou, et al., 2011). In Finland, the first AD facility was a wastewater purification test plant, which operated 1902 – 1904. The biogas production began first time in 1932 in a wastewater treatment plant in Helsinki (Lampinen, 2009). The substrates of biogas production were set under the research microscope on 1930s by Buswell, while Ducellier and Isman started development of biogas machinery. For long, essential purpose of AD was pollution prevention of wastewater sludge and decreasing amount of waste. Later in the 20th century, higher energy prices and environmental legislation led to development of biogas production, processing and usage. Today, AD is a well-studied and developed process, which serves as a standard application for stabilization of sewage sludge and treatment of organic waste from different sources e.g. food industry and agriculture (Al Seadi, et al., 2008). (Deublein & Steinhauser, 2011)

In Europe, the forerunner countries in biogas sector with thousands of modern biogas plant installations include Germany, Austria, Denmark and Sweden. Combined heat and power production (CHP) and use as a transportation fuel are standard applications of biogas use in the pioneer countries. Asian countries, China and India in front, have a great number of simple technology family-size digesters. In China alone, the number of rural household devices is estimated to be up to 18 million. In American continents, development of biogas production technologies has followed the European example although the success has not been on the same level. (Deublein & Steinhauser, 2011) In 2012, heat production from biogas in Finland was 408.8 GWh, power production was 159.6 GWh and the energy amount wasted in flare combustion of biogas was also significant: 114.5 GWh (Huttunen & Kuittinen, 2013). The sum of heat and power production, 568.4 GWh, equals to 0.15% of total energy use while the overall biogas potential from wastes in year 2015 is estimated to be between 6 700 and 18 000 GWh per year (Asplund, et al., 2005).

1.2 Background of digestate applications

The thorough research on biogas production chain has recently extended to optimizing usage of digestion residue, digestate. In terms of waste reduction, emissions and economy, the digestate is an increasingly important factor in biogas production and, thus, should have a useful purpose as well. (Monnet, 2003) For example, the emission study on biogas chain by Sinkko et al. (2012) proves the importance of digestate application on greenhouse gas emissions. Environmental benefits of digestate applicability have also been acknowledged in the legislations and directives of e.g. the EU (Teglia, et al., 2011) (Saveyn & Eder, 2014).

Due to high nutrient value, the digestate is often considered as a potential substitute for synthetic fertilizers, use of which has increased dramatically in agriculture since the 50's. Further growth of human population will increase demand of food

production and, thus, energy and fertilizers (Maunuksela, et al., 2012). Production of inorganic fertilizers is not only energy and emission intensive but also non-renewable: especially phosphorous is an exhausting fossil resource (Syers, et al., 2011). The scarcities of fossil fuels and non-renewable nutrient resources have already resulted in increased prices of inorganic fertilizers and, hence, improved competitiveness of organic fertilizers. In addition, inappropriate and excessive inorganic fertilizer usage in agriculture has resulted in eutrophication at e.g. Baltic Sea and inland waters in Finland (Uusitalo, et al., 2007). Digestate is often considered a fertilizer due to notable content of nutrients and organic substances (Clements, et al., 2012).

The components of raw digestate, the output of AD process, can vary broadly. The contents are dependent on the feed matter and the process conditions, and determine the application and requirement for post-processing. Today, the general options for the digestate use are landscaping, combustion and fertilization, the last of which is often the most attractive option due to organic and nutrient content (Hahn & Hoffstede, 2010). On the other hand, agricultural utilization is controlled by strict legislation and public perception of hygienic and pollutant issues. In Finland, only around dozen biogas plants were merchandizing digestate products in 2011 (Marttinen, et al., 2013) while in Germany, success of biogas production in some communities has led to excess of digestate fertilizers (Hahn & Hoffstede, 2010).

1.3 Research problem and objective

Currently in Finland, around 10 companies merchandize certified digestate products in the local markets (Evira, 2013a). However, none of the products or production processes has gained wide success due to low prices of inorganic fertilizers, unawareness of the product and variance of qualities. The digestate is often a zero-value or a very low value product. (Partanen, 2010) Importance of the standardization of digestate products is growing as the biogas production in agricultural and co-generation plants has been raising rapidly on the last years (Huttunen & Kuittinen, 2013) due to support to renewable and local energy sources. In order to optimize waste treatment and, thus, the feasibility of whole biogas production chain, the digestate should be considered a product instead of waste.

The objective of this Thesis is to assess energy efficiency and GHG emissions in different application chains of digestate, which are viable in Finland. These environmental factors provide critical information on digestate applicability also for the economic feasibility assessments, which finally determine the usability. The environmental and economic benefits of digestate use are not clear as uncertainties are involved in e.g. energy demand of treatment processes, ammonia emissions in land applications and variance in digestate contents (Al Seadi, et al., 2008). Additionally, as performance data of individual processes is obtained, comparison of different process paths is enabled. Thus, another object is to build an effective excel-tool for convenient data processing, which can be applied with more specific boundaries as well.

1.4 Method, outline and structure of Thesis

The Thesis is outlined to present information on digestate production and, as a main research, determine energy efficiency and GHG emissions in different utilization chains of digestate. The chains are studied from raw digestate, an untreated residue of AD, to application, as illustrated in Figure 1.3. The emphasis is set on possible digestate end products in Finland while the technology study bases on the world top level, which is usually represented in Europe. The main properties of digestate are monitored as well, since the energy efficiencies, determined as *primary energy demands (PEDs),* and GHG emissions, as *CO2 equivalents*, of processes and applications are dependent on e.g. mass and nutrient content of the matter. Chapter two of this Thesis covers the basic information about biogas, AD substrates and anaerobic digestion since the properties of digestate, the secondary product, are essentially dependent on biogas production. The sequential chapter discusses basics of digestate, its contents and its applications.

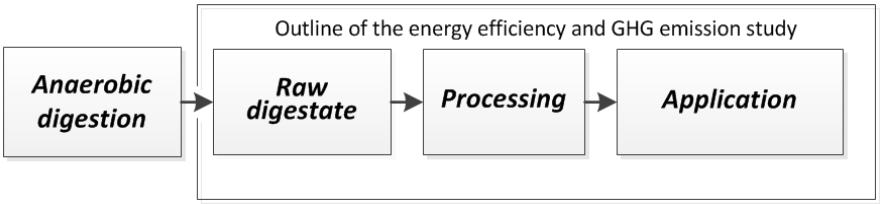

Figure 1.3 Outline of the energy and GHG study in the digestate production flow.

Chapter four presents the alternatives for digestate processing and applications, for which the next chapter provides separate energy and GHG emission data. Also, the scheme of application chains evaluated in the calculations is introduced in the latter as well as the primary energy factors and specific emission factors. These are used to convert values of secondary energy carriers to primary energy demands and CO_2 equivalents per tonne raw digestate, which enables linking the processes and applications together. The studied applications are:

- *Soil improver-growing media (SIGM)*
- *Solid fuel (fertilizer pellet)*
- *Ammonium sulphate fertilizer*
- *Liquid fertilizer*

An excel-tool is built to efficiently link, process and compare the data, covering primary energy balances, CO_2 equivalent emissions, conversion factors and digestate compounds. The principles of calculation and chain specific results of PED and GHG emission are presented in Chapter six while few factors, e.g. energy recovery, chemical hygienization and raw digestate properties, are studied separately from the main calculations. The results are summed up, the sensitivities analyzed and the final conclusions drawn in the last three chapters.

2 BIOGAS

This Chapter discusses basics of biogas, anaerobic digestion and biogas plants. Since biogas is the primary product of anaerobic digestion process, the properties of secondary product and research subject of this Thesis; digestate, are commensurate to used substrates and process conditions. The information is collected from several literature sources, most referred of which are Deublein's & Steinhauser's book *Biogas from Waste and Renewable Resources: An Introduction* (2011) and *Biogas Handbook* (2008) by Al Seadi et al. The study on biogas plants focuses on European and especially Finnish plant types: The categorization of the plants bases on the register of Finnish biogas plants (Huttunen & Kuittinen, 2013).

2.1 Definition and properties of biogas

Biogas is a product gas of anaerobic digestion (i.e. digestion in the absence of oxygen) of organic matter and consists mainly of *methane (CH_4)* and *carbon dioxide (CO_2)* (Ministry of employment and the economy, 2011). Biogas is a flammable gas as its methane content is higher than 45 percent: 45 – 75 % of the volume, while corresponding proportion for natural gas can be more than 98. The remaining volume of biogas is mostly carbon dioxide. (Deublein & Steinhauser, 2011)

In addition to methane and carbon dioxide, biogas contains smaller amounts of *nitrogen (N_2), hydrogen sulphide (H_2S)* and *oxygen (O_2)*, and traces of *ammonia (NH_3)* and *hydrogen (H_2).* Also, biogas from agricultural sources and landfills may contain *chlorofluorocarbons (CFCs)* while *siloxanes* may end up to sewage and landfill gases. Of elements above, hydrogen sulphide, CFCs and siloxanes are the most harmful substances in biogases as they are highly corrosive. Features for different biogases and natural gas in Finland can be seen in Table 2.1 (Deublein & Steinhauser, 2011). (Persson, et al., 2006)

The Wobbe index (*kWh nm^{-3}*) is an indicator of energy content, as well as quality, of the methane gases. The Wobbe index can be computed from *higher* or *lower heating value* (*HHV* or *LHV*, a.k.a. net calorific value) (*kWh nm^{-3})* by a formula

$$W_{h/l} = \frac{q_{vol,h/l}}{\sqrt{d_r}} \quad (1)$$

where

$W_{h/l}$ *the higher/lower Wobbe index, kWh nm^{-3}*
$q_{vol,h/l}$ *higher/lower heating value by volume, kWh nm^{-3}*
d_r *relative density compared to air*

The Wobbe index of a methane gas is determined by the methane content: The value of the lower Wobbe index for biogas varies from 4.7 to 7.9 kWh nm^{-3}, as presented in Table 2.1. For Russian natural gas the value is 11.7 kWh nm^{-3}. Comparing different biogas sources, the AD processes in sewage treatment and in agricultural substrate facilities generate better gas quality than landfills. (Deublein & Steinhauser, 2011)

Table 2.1 Physical properties of sewage gas, agricultural gas, landfill gas, for Finnish gas grid and Russian natural gas. (Deublein & Steinhauser, 2011)

Feature	***Unit***	***Biogas***			***Natural gas***	
		Sewage gas	*Agricultural gas*	*Landfill gas*	*Requirements of Finnish gas grid*[I]	*Group H (Russian, used in Finland)*
Methane, CH_4	*vol-%*	65 – 75	45 – 75	45 – 55	≥85 *mol-%*	98.31
Higher hydrocarbons, H_nC_m	*vol-%*	*n.s.*	*n.s.*	*n.s.*	≤9 *mol-%*	0.3
Hydrogen, H_2	*vol-%*	*traces*	0.5	0	-	-
Carbon dioxide, CO_2	*vol-%*	20 – 35	25 – 55	25 – 30	≤2.5 *mol-%*	0.08
Nitrogen, N_2	*vol-%*	3.4	0.01 – 5	10 – 25	-	0.81
Oxygen. O_2	*vol-%*	0.5	0.01 – 2	1 – 5	*traces*	0.05
Hydrogen sulphide, H_2S	*mg/nm^3*	< 8000	10 – 30.000	< 8000	≤15	5
Ammonia, NH_3	*mg/nm^3*	*traces*	0.01 – 2.5	*traces*	-	0
CFCs	*mg/nm^3*	0	20 – 1000	*n.s.*	-	0
Lower Wobbe Index[II]	*kWh/nm^3*	6.3 – 7.9	5.3 – 7.0	4.7 – 5.2	-	13.2
Lower heating value (LHV)	*kWh/nm^3*	6.0 – 7.5	5.0 – 7.5	4.5 – 5.5	-	9.98
Lower heating value (LHV)	*MJ/kg*	18.6 – 23.3	15.5 – 23.3	12.8 – 15.6		49.2
Relative density (to air)		0.9	0.9	1.1	-	0.57

I (Gasum Oy, 2012)
II *Computed with equation 1*

To set energy value of biogas against fossil fuels in different physical states, mass related energy content should be evaluated. Higher or lower heating value in unit *MJ/kg*, for biogas and natural gas is determined by a formula

$$q_{h/l} = \frac{q_{vol,h/l}}{d_n} * 3.6 \qquad (2)$$

where

$q_{h/l}$ *higher/lower heating value by mass, MJ kg^{-1}*
d_n *normal density, kg nm^{-3}*

Presented in Table 2.1, mass related lower heating value of biogas fluctuates between 12.8 and 23.3 MJ/kg. Thus, biogas can reach the level of coal (wet basis), 22.7 MJ/kg, while the LHV of crude oil is clearly higher; 42.7 MJ/kg. As for Russian natural gas, the value is the highest, 49.2 MJ/kg. (Boundy, et al., 2011)

2.1.1 Energy efficiency of biogas

Typically 70 % of energy of the feedstock is converted to the biogas in AD process (Møller, et al., 2011). The literature survey by Havukainen, et al. (2013) indicates variable results from different energy performance researches of biogas production: ratio of energy input to output varies between 20 % and 64 % while output/input ratios set between 1.8-13.1. The wide range of results is due to varying calculation methods and system boundaries. According to one of the most comprehensive studies by Berglund & Börjesson (2006), in Swedish conditions the energy input to production of biogas typically corresponds 20 – 40 % of the output energy of the gas. Of energy input, operation of biogas plant consumes the majority, 40 – 80 %. An example of energy balances in a biogas plant is presented in Figure 2.1 (Møller, et al., 2011).

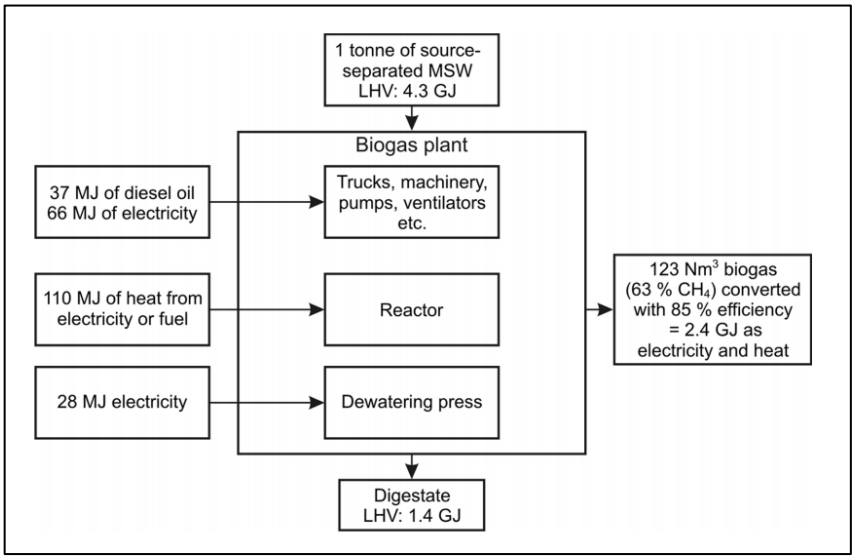

Figure 2.1 Energy balance of the processes and materials in a theoretical biogas plant processing MSW. Adapted from Møller et al. (2011).

2.1.2 Greenhouse gas emissions from biogas production and use

Biogas can be considered as a nearly carbon neutral energy source since the carbon cycle is closed within a short time frame: the carbon was recently bound to biomass from the atmosphere and is now released in combustion of biogas or recycled as a digestate. The biomass used in biogas production is generally easily degradable as a result of fast growing. Thus the timeframe of carbon cycle is significantly shorter, compared to e.g. wood biomass, and the life cycle emission peak at combustion is less significant. Also, biogas often substitutes fossil fuel use, which results in decrease of GHG emissions in overall energy production. Furthermore, if digestate of biogas production is used as a fertilizer, significant emissions from production of substituted fertilizer are avoided (Møller, et al., 2009). (Al Seadi, et al., 2008)

Gathering gases in controlled AD of biomass instead of direct release from natural decomposition processes also reduces GHG emissions. Firstly, natural processes would emit methane (GWP 25), which is collected in anaerobic reactor as a part of biogas and turned into carbon dioxide in combustion. Secondly, controlled AD

decreases formation of nitrous oxide (N_2O, GWP 298), which also occurs in uncontrolled processes. In landfills, direct release of methane and nitrogen gases from degradation processes can be reduced by a landfill gas collection system. (IPCC, 2007) (Latvala, 2009)

Compared to composting, CO_2 release of AD is significantly lower due to substitutive methane formation. According to the Gibbs free energy in chemical processes of composting and AD, 19 times less energy is released in the anaerobic digestion (Scholwin & Nelles, 2013). Moller, et al. estimated in their study (2009) the global warming factor (GWF) of a specific type of AD facility to set between -95 and -4 kg CO_2-eq per tonne of wet waste substrate, where minus indicates decrease in warming effect.

2.1.3 ABPR and IED

In the EU, numerous statutes concern treatment of different waste types, AD and digestate applications. Generally, the regulation on the use of *animal by-products (ABPR)* (EC No 1069/2009) and *the industrial emission directive* (IED) are concerned the most important in biogas production. The aim of the animal by-product regulation is to prevent spread of transmissible spongiform encephalopathies (TSE) and foot and mouth disease e.g. via digestate. The regulation by GWP 100 divides animal by-products in three categories by level of health risk: biogas plants mainly treat, after required pretreatment, category 3, the least risk by-products, and category 2, the epidemic risk by-products. For category 1 material, only derived products are suitable for AD. (EU No 142/2011) Also, appropriate sanitation conditions, particle size and number of indicator organisms are defined for categories 2 and 3, see Table 2.2 below. (Al Seadi & Lukehurst, 2012)

Table 2.2 Examples of required pretreatment processes for selected animal by-products defined in the Regulation EC1069/2009. (Al Seadi & Lukehurst, 2012)

Animal by-product for AD	***Required pretreatment***	***Category***
Manure and digestive tract content from slaughterhouse	*No pretreatment*	2
Milk and colostrums	*No pretreatment*	2
Perished animals	*Pressure sterilization*	2
Slaughtered animal, not intended for human consumption	*Pressure sterilization*	2
Meat-containing wastes from foodstuff industry	*Pasteurization*	3
Slaughterhouse wastes from animas fit for human consumption	*Pasteurization*	3
Catering waste, except waste from international transports	*In accordance with national regulation*	3

The industrial emission directive (IED) (2010/75/EU) was enacted on year 2010 to combine EU regulations of environmental protection and to bind EU countries to requirements of *best available technologies* (BAT). Essentially, the directive defines BATs for all significant industries and instructs implementation of those to national legislations of all EU countries. After adoption of *BAT Reference Document* (BREF), member states are obligated to bring the technology to practice within four years. In 2014, the anaerobic digestion technology is concerned by BREF of waste treatment industries (EC, 2006a) from year 2006 while review for a new document has started. (Panek-Gondek, 2012)

2.2 Anaerobic digestion

Anaerobic digestion (AD) is a biochemical process in which methane and carbon dioxide are produced by degrading organic matter in the absence of oxygen. In addition to biogas production, AD is a proper method for controlled organic waste treatment and increasing fertilizer value of organic matter (Paavola, et al., 2009). Also, AD occurs in the nature e.g. at bottoms of lakes and in landfills (Stamatelatou, et al., 2011). Typical duration of AD, a.k.a. retention time, in Finnish biogas plants is 12 to 30 days depending on the substrate and process conditions (Latvala, 2009). The process can be divided in four steps, which are presented in Figure 2.2 below.

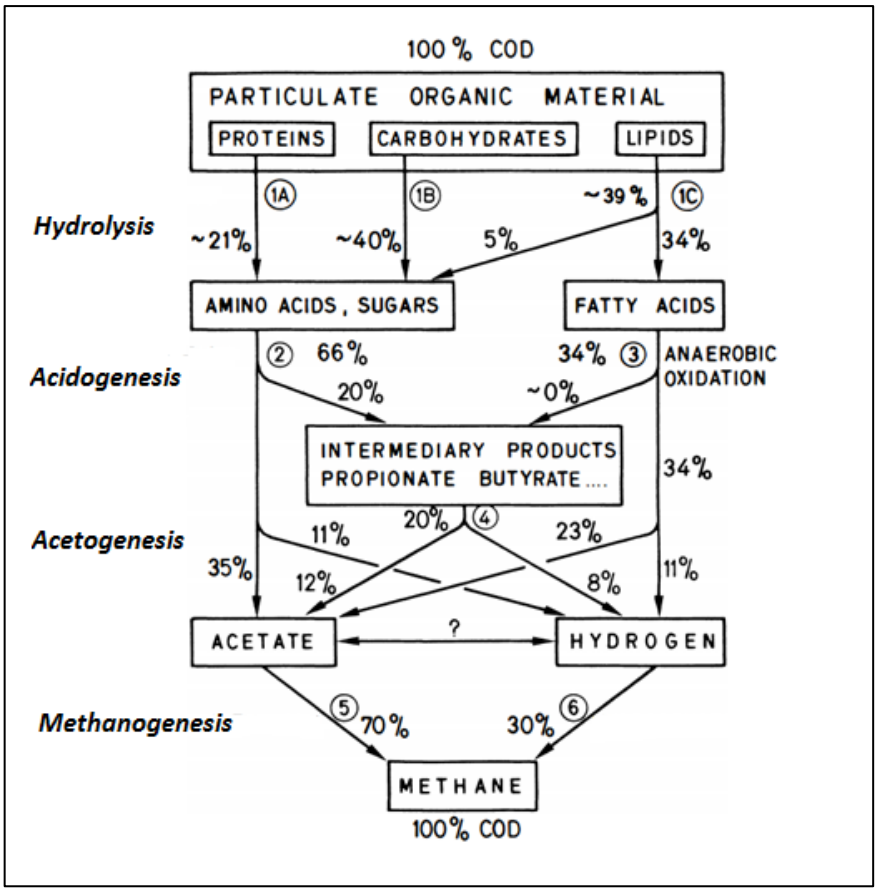

Figure 2.2 Chemical processes and chemical oxygen demands (COD) indicating flow of organic compounds in anaerobic digestion of sewage sludge. Kaspar & Wuhrman cited by Gujer & Zender (1983).

2.2.1 Chemical processes in anaerobic digestion

On the first step, *hydrolysis*, the substrate disintegrates to complex polymers; mainly carbohydrates, proteins and lipids. Further, carbohydrates depolymerize into short-chain sugars, proteins into amino acids and lipids into fatty acids and glycerine by extracellular enzymes excreted by fermentative bacteria. During hydrolysis, carbohydrates break down within a few hours, proteins and lipids within a few days. Stronger compounds, such as lignin and lignocellulose degrade slowly and only partially without pretreatment. (Deublein & Steinhauser, 2011)

Over the second phase, *acidogenesis*, the formed monomers are treated with anaerobic bacteria and consequently degrade to short-chain organic compounds, such as volatile fatty acids and alcohol (Stamatelatou, et al., 2011). Also, significant amounts of carbon dioxide and hydrogen are produced. Since the formation of acids is rapid, danger of acid accumulation is present during acidogenesis if the following degradation is delayed. In the following step *acetogenesis*, acetogenic bacteria convert organic molecules produced in last phase to acetic acids, carbon dioxide and hydrogen through endergonic reactions in a low hydrogen partial pressure. (Deublein & Steinhauser, 2011)

Methanogenic microorganisms generate methane from hydrogen, carbon dioxide and acetates during the last phase of AD, *methanogenesis*. Acetogenesis and methanogenesis are complementary to each other: since formation of H_2, CO_2 and acetates occurs predominantly in a low hydrogen partial pressure, successful methanogenesis is required to consume the produced hydrogen (Deublein & Steinhauser, 2011). Due to balance to acetogenesis and the longest duration of all five processes, methanogenesis is a critical step in completing anaerobic digestion process. According to Al Seadi, et al. (2008) 70 % of the methane is of acetate and 30 % is of hydrogen and carbon dioxide origin. Examples of methane producing chemical reactions are presented in Table 2.3 below.

Table 2.3 Examples of methane producing chemical reactions during methanogenesis and Gibbs free energy ΔG_f for those; minus sign indicates spontaneous reaction. Methyl is an intermediate product in methanogenesis. (Deublein & Steinhauser, 2011)

Substrate type	***Chemical reaction***	***ΔG_f (kJ kmol^{-1})***
CO_2	$4\ H_2 + CO_2 \rightarrow CH_4 + 2\ H_2O$	-131.0
CO_2	$4\ HCOO^- + H_2O + H^+ \rightarrow CH_4 + 3\ HCO^-_3$	-130.4
Acetate	$CH_3COO^- + H_2O \rightarrow CH_4 + HCO^-_3$	-30.9
Methyl	$4\ CH_3OH \rightarrow 3CH_4 + HCO^-_3 + H^+ + H_20$	-314.3

2.2.2 Factors affecting anaerobic digestion

Optimum performance of AD is dependent on many parameters, such as process temperature, pH value, substrate composition and organic load. Further, substrate composition includes several critical factors affecting the process balance, e.g. quantity and type of organic compounds and toxic element content.

2.2.2.1 Temperature

The temperature has substantial influence on the methane yield and retention time of the process. Operation temperatures of AD can be divided in three groups by optimum performance of different bacteria: *psychrophilic* microorganism at under 20 °C (Al Seadi, et al., 2008), *mesophilic* at 32 – 42 °C and *thermophilic* at 48 – 55 °C. Use of psychrophilic operation is uncommon due to long retention time. Thermophilic process provides faster and higher efficiency operation than mesophilic, as seen in Figure 2.3. On the other hand, thermophilic is less stable and demands 10 – 30 % (Latvala, 2009) more energy to preserve the temperature. Another pro for thermophilic process is that higher operation temperature removes pathogens efficiently. (Deublein & Steinhauser, 2011)

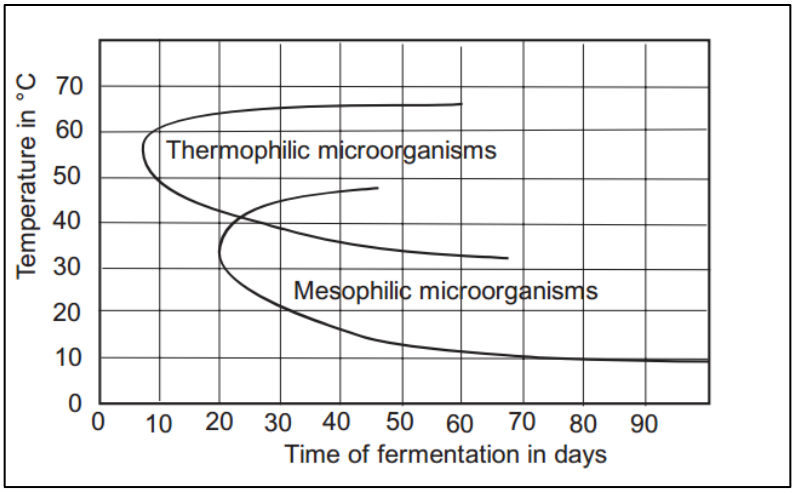

Figure 2.3 Relation of temperature and retention time for thermophilic and mesophilic microorganisms. Adapted from Deublein & Steinhauser (2011).

2.2.2.2 The pH

The pH value indicates level of acidity or alkalinity of the processed material. In AD, the pH affects e.g. performance of extracellular enzymes and disintegration of compounds, which are important for the entire process (Al Seadi, et al., 2008). Acidogenic bacteria generate acids at low pH values 5 – 6.5 (Stamatelatou, et al., 2011) while the optimum value for operation of methanogenic microorganisms, i.e. methane production, is between 6.7 and 7.5. Thus, many modern plants feature two different reaction stages: lower pH acidogenesis stage before higher pH methanogenesis stage. Also, the pH value in AD is controlled by two natural buffer systems; one for increased acidity and one for decreased. (Deublein & Steinhauser, 2011)

2.2.2.3 Substrate composition and disintegration

Substrate composition is an essential and complex factor of anaerobic digestion, since the process requires particular substances in particular phases and conditions. Firstly, decomposition rate of different organic compounds, such as sugars, fats and cellulose, is highly variable. This affects the methane yield: more reduced the carbon is, higher is the methane content in biogas (Stamatelatou, et al., 2011). The AD can be improved by disintegration of organic elements before or during the process. Destruction of the cell structure extends surface area and lowers viscosity of material increasing heat and material transfer. The influence to biogas yield can be seen in Figure 2.4. (Deublein & Steinhauser, 2011)

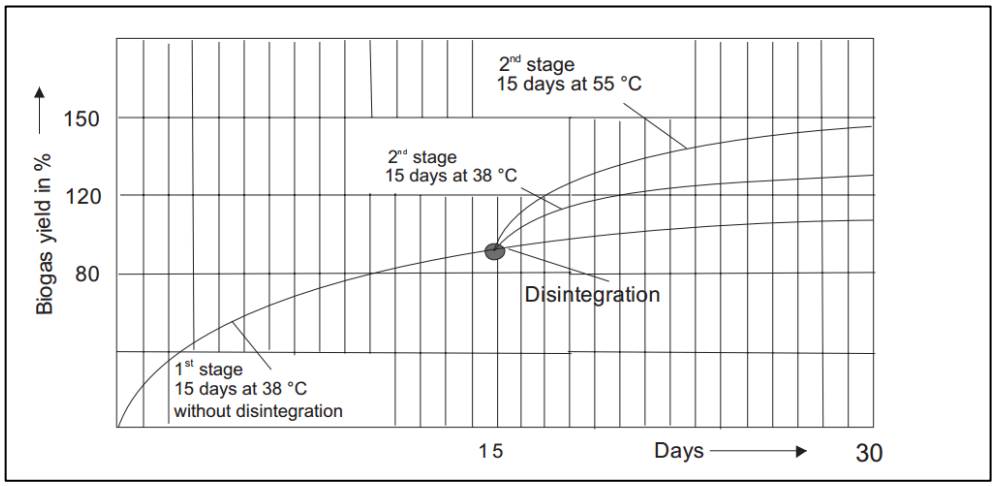

Figure 2.4 Influence of disintegration to biogas yield of sewage sludge. Adapted from Deublein & Steinhauser (2011).

Secondly, feed of a possibly lacking substantial substance is often required in AD reactor since absence of initial compound or intermediate product may inhibit the metabolism (Deublein & Steinhauser, 2011). Ammonia, especially free ammonia, and volatile fatty acids are important middle elements affecting the stability of AD process. Accumulation of ammonia intrudes methane fermentation and excess of volatile fatty acids reduces further degradation. (Al Seadi, et al., 2008)

Many elements in the substrate, such as long chain fatty acids, metals and phenols, could be toxic to AD depending on concentrations and process conditions. For example, heavy metals have a double role in AD process; they serve as elements in vital enzymes while they tend to accumulate at toxic concentrations. Also oxygen acts as a toxic element for anaerobic bacteria. Oxygen reacts with enzymes producing toxic free radicals, concentration of which is dependent on presence of other enzymes removing the toxic oxygen radicals. (Stamatelatou, et al., 2011)

2.2.2.4 Organic volume load and HRT

Design of biogas reactor is based on estimated *organic volume load*. Organic volume load indicates mass of organic dry matter in substrate per reactor volume and time unit. Optimum organic volume, usually 1 – 3 kg_{ODM} m^{-3} d^{-1}, enables the best possible methane production on desired time period. If the load is too low, operation is not

economic since too much water is fed to the reactor and methane production is reduced due to lack of organic matter. On the other hand, when the organic load is too high, pumping of biomass becomes difficult and the AD process is limited due to lowered material transfer. (Deublein & Steinhauser, 2011)

In addition, *hydraulic retention time* (HRT) is a commonly used term concerning volume load of biogas reactor, indicating average time period, which substrate stays in a digester. HRT is determined as a ratio of digester volume to digester feedstock volume per time unit. For example, for cattle manure an average HRT in mesophilic digestion is 12 to 18 days. (Wellinger, 1999)

2.3 Substrates

Basically, biogas can be produced through anaerobic digestion from any biomass, which consists mainly of carbohydrates, proteins, fats, cellulose and hemicellulose. The significant properties of a substrate include content of organic substances suitable for fermentation process, dry matter content, nutritional value of organic matter and content of harmful substances. For example, lignin is a slowly degrading organic substance and therefore not proper for biogas production. (Deublein & Steinhauser, 2011) The substrates that can be used for biogas production include (Al Seadi, et al., 2008):

- Animal manure and slurry;
- Agricultural residues and by-products;
- Digestible organic wastes from food and agro industries (vegetable and animal origin);
- Organic fraction of municipal solid waste (MSW) and from catering (vegetable and animal origin);
- Sewage sludge;
- Dedicated energy crops (e.g. maize, miscanthus, sorghum, clover); and
- Organic waste from other industries e.g. paper, leather and textile industries.

The biogas yield of different substrates is highly variable as seen in Table 2.4 (Al Seadi, et al., 2013a). Animal manure has a rather low yield and, thus, is often mixed to substrates with high methane yield, such as oil and alcohol wastes (Al Seadi, et al., 2008). Organic fraction of municipal solid waste could be perfectly suitable substrate for AD but the matter often contains adverse amount of impurities, which affect the process and digestate quality (Monnet, 2003). Also, the yield of a particular source is highly dependent on, for example, the time of harvest, weather conditions, the bioreactor loading and the residence time (Deublein & Steinhauser, 2011).

Table 2.4 Contents of dry matter, organic dry matter and biogas yields of selected AD substrates. (Al Seadi, et al., 2013a)

Substrate	*Dry matter (DM) % of fresh material*	*Organic dry matter (ODM) % of DM*	*Methane yield $m^3\ kg^{-1}_{ODM}$*
Energy crop (Grass silage)	15 – 40	90	0.3 – 0.45
Fruit wastes	15 – 20	75	0.25 – 0.5
Fish oil	90	90	0.8
Flotation sludge	5	80	0.54
Cattle slurry	8	80	0.2
Cattle manure, solid	20	80	0.2
Pig manure, solid	20	80	0.3
Poultry droppings	5	80	0.3
Food remains	10	80	0.5 – 0.6
Wastewater sludge	5	75	0.4

Recently scientists have also studied possibility to use lignocelluloses, such as wood and grasses, or cultivated algae as an AD substrate (Deublein & Steinhauser, 2011). Lignocellulose-containing biomass is one of the most abundant resource on Earth but the substrate should often be pretreated physically, chemically or biologically to disintegrate the structure of cellulose in microfibrils and other binders. Pretreatment increases methane production due to extension in surface area and decrease in time of fermentation. (Mudhoo, 2012)

Micro-algae is grown by photosynThesis, using atmospheric CO_2, water and sunlight and producing high polysaccharides and lipid content, which results in greater energy yield than of energy plants and trees. The cultivation basins of algae are fed with nutrient-rich wastewater to increase the number of micro-algae continuously. Therefore, part of the grown algae could be constantly removed to AD reactor to produce biogas. (Debowski, et al., 2013)

2.4 Biogas plants

Usually, biogas is produced in an AD reactor of a biogas plant while gas from natural degradation is also collected, in practice from landfills. Substrate properties determine the essential technical process factors: batch or continuous process, single or multistage digestion, dry (DM > 15 %, in some definitions > 20 % (Braun & Wellinger, 2003)) or wet fermentation (DM < 15 %), and temperature stage. At first, development of agricultural and wastewater biogas plants was the most intense due to extensive supply of organic material while recently centralized plants have gained favor (Fuchs & Drosg, 2013). The strengthening environmental legislation has led to increasing recycling of different organic waste streams. Another common biogas production facility is a landfill gas recovery plant. In 2009, there were 195 large AD plants and in 2010, 7500 smaller agricultural and co-digestion plants in the EU member states (Saveyn & Eder, 2014). (Al Seadi, et al., 2008)

Generally all biogas plants are equipped with a substrate preparation tank, a digester tank, a digestate storage tank and a biogas handling facility (Luostarinen, 2013). In the preparation tank, the substrates are mixed and, if required, heated up to demolish pathogens from the substrate. When desired substrate quality is achieved, it is fed to the digester tank, where the AD process occurs in suitable conditions and the biogas is produced. After AD, the digestate is led to a storage tank and the gas to an upgrading facility or direct energy use. Common additional appliances are substrate preprocessing, e.g. crushing or impurity removal unit and division of digestion to two reactors. A typical biogas plant, featuring also biogas collection from late digestion in digestate storage tank, is introduced in Figure 2.5. (FNR, 2009)

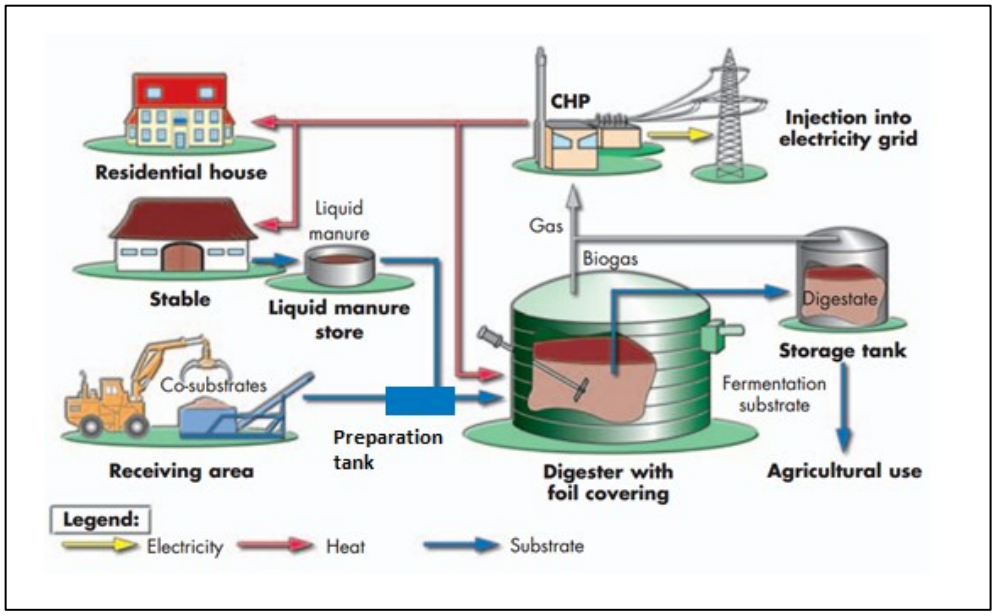

Figure 2.5 Commodity flows in a typical co-digestion biogas plant. Adapted from FNR (2009) and edited: preparation tank added.

2.4.1 Agricultural biogas plants

Agricultural biogas plants are fed with biomass of agricultural origin: agricultural residues, energy crops and livestock manure and slurries. Main advantages of agricultural biogas facilities are availability of feed material, reduction of manures and slurries, and direct use of digestate as a fertilizer. On the other hand, AD process improves nutrient value of animal manures and slurries, which also are used as fertilizers untreated. Typical agricultural plants are relatively small, utilize feedstock from their own or nearby supply and are equipped with simple technology, which farmer alone can operate and service (Deublein & Steinhauser, 2011). A general agricultural digester is presented in Figure 2.6.

In Asia, most of the plants are family-size and feature simpler technology than in Europe, where advanced farm-size digesters are common. In Europe, forerunner countries in agricultural biogas include Germany, Austria and Denmark. Finnish agricultural biogas production has been small-scale: in year 2012 the production, as seen in Figure 2.7, was around 1 million cubic meters compared to total biogas production of 150 million m^3. (Huttunen & Kuittinen, 2013). (Al Seadi, et al., 2008)

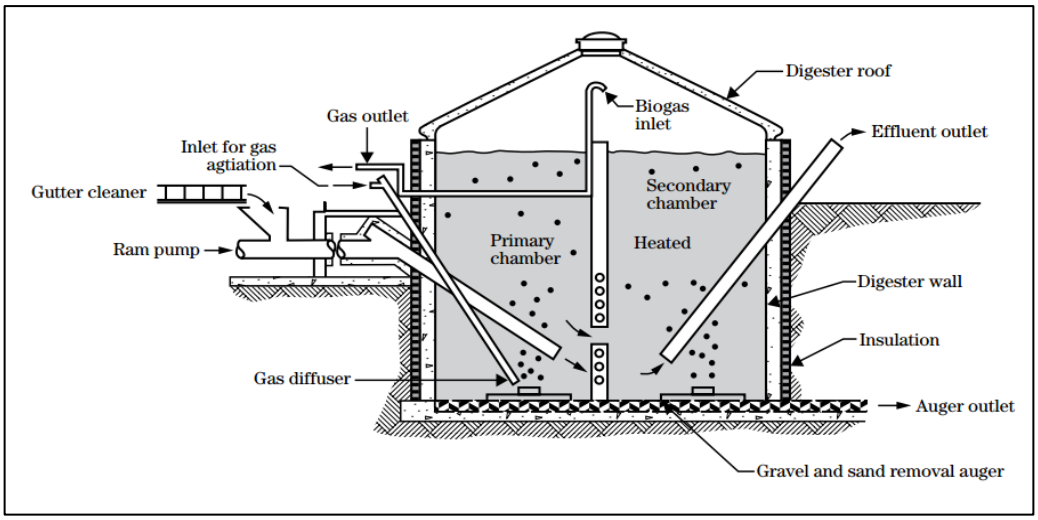

Figure 2.6 Components of a general agricultural two-stage digester. Adapted from NRCS (2009).

The biogas production process is either batchwise or continuous. In batch process the digester is filled up once and after desired retention time, the digestate is removed all at once. Nowadays majority of agricultural biogas plants utilize latter "flow-through processes" due to independent operation and a higher gas yield (Deublein & Steinhauser, 2011). However, the choice of process model is dependent on the feed material. In dry fermentation the substrate is often too thick to be pumped; in Germany batch process is mostly used method in dry fermentation while majority of the plants base on wet and mesophilic fermentation and feature semi-continuous process (FNR, 2009).

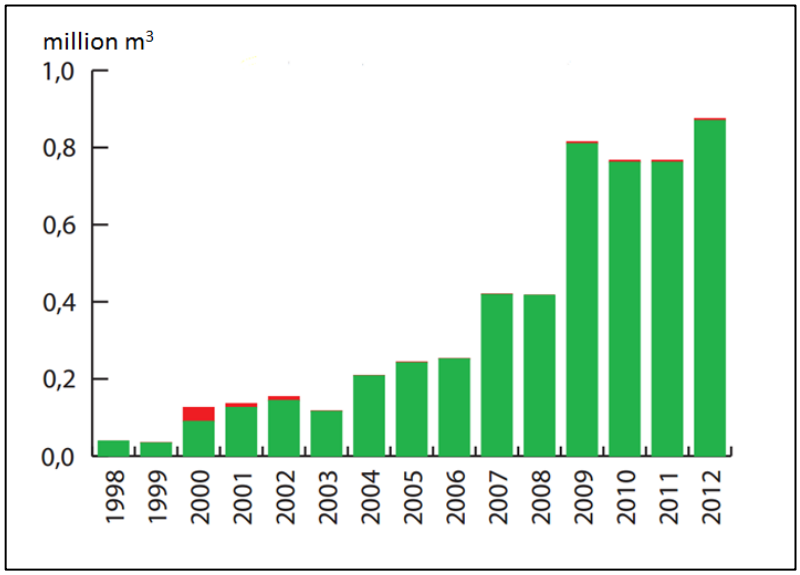

Figure 2.7 Biogas produced, in unit million m^3, in agricultural biogas plants in Finland 1998 – 2012. Red (on top) indicates amount to flaring and green to utilization. Adapted from Huttunen & Kuittinen (2013).

2.4.2 Centralized co-digestion plants

Centralized co-digestion stands for AD which simultaneously treats substrates from several sources and sites. In most cases co-digestion is based on mixing major substrate, e.g. agricultural manure or sewage sludge, to additional minor resources. Technically centralized co-digestion plants are more advanced than agricultural facilities. They are larger, substrates require more pretreatment and the process should be monitored and controlled more intensively. (Braun & Wellinger, 2003) In Finland, co-digestion has increased rapidly on the last years, see Figure 2.8, and contrary to central Europe, produces multiple amount of biogas compared to agricultural plants (Huttunen & Kuittinen, 2013). This also generates difference in typical digestate properties as centralizer plants often process e.g. MSW (Partanen, 2010).

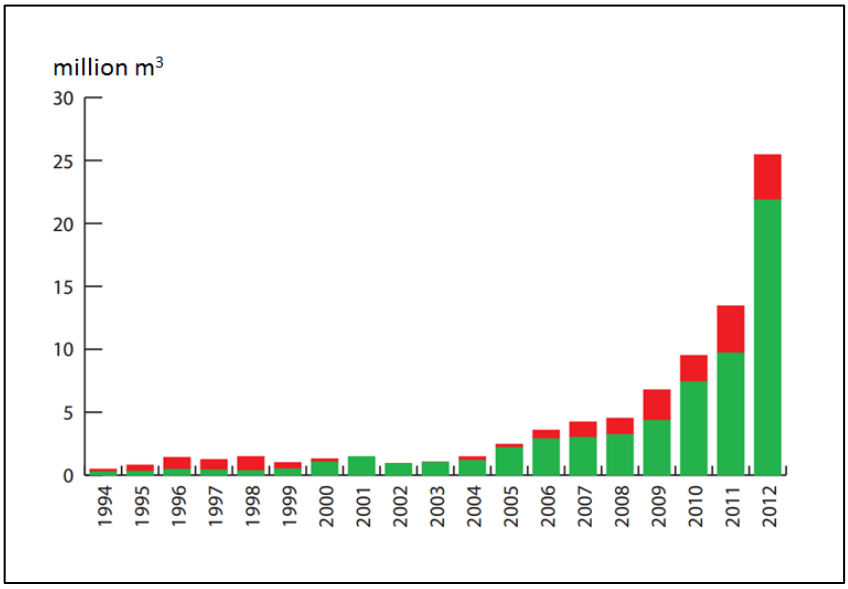

Figure 2.8 Biogas produced, in unit million m^3, in co-digestion biogas plants in Finland 1994 – 2012. Red (on top) indicates amount to flaring and green to utilization. Adapted from Huttunen & Kuittinen (2013).

According to Braun & Wellinger (2003), main drivers of the co-digestion are rise in biogas yield of manures and slurries, and intensified biogas production at wastewater treatment plant. Another benefit is a decrease in investment and operation costs per unit of biogas produced (Al Seadi, et al., 2008). On the other hand, central location requires longer transportation distances for material flows. In addition, Monnet (2003) lists increased pumpability of solid materials and improved disintegration of certain materials while downside of the centralized production is dependency on several substrate suppliers. (Braun & Wellinger, 2003)

Using various substrate sources in co-digestion results in uniform availability of feedstock throughout the seasons and controllability of water, organic and nutrient content. Thus, a stable process and a high fertilizing quality are achieved (Braun & Wellinger, 2003). Numerous potential sources of organic materials, e.g. organic municipal solid waste (Latvala, 2009) or slaughterhouse waste (Ek, et al., 2011), are insufficient, unstable or too expensive to be utilized alone. According to Al Seadi, et

al. (2008), hundreds of biogas plants around the world were processing organic fraction of municipal solid waste in 2008.

2.4.3 Wastewater treatment plants

In *a wastewater treatment plant* (WWTP) the main purpose of AD is to stabilize the primary and secondary sewage sludge, remove pathogens and reduce amount of waste. Digested biogas is an extra product which is often used to fuel main WWTP processes (EPA, 2012). On the first half of 20th century anaerobic digestion, in addition to composting, became a standard technology for WWTPs (Al Seadi, et al., 2008) and on the latter half, biogas production in the treatment plants spread due to energy crises (Deublein & Steinhauser, 2011). Also in Finland, biogas has been produced in WWTPs for decades; progress from the 90's is presented in Figure 2.9 (Huttunen & Kuittinen, 2013).

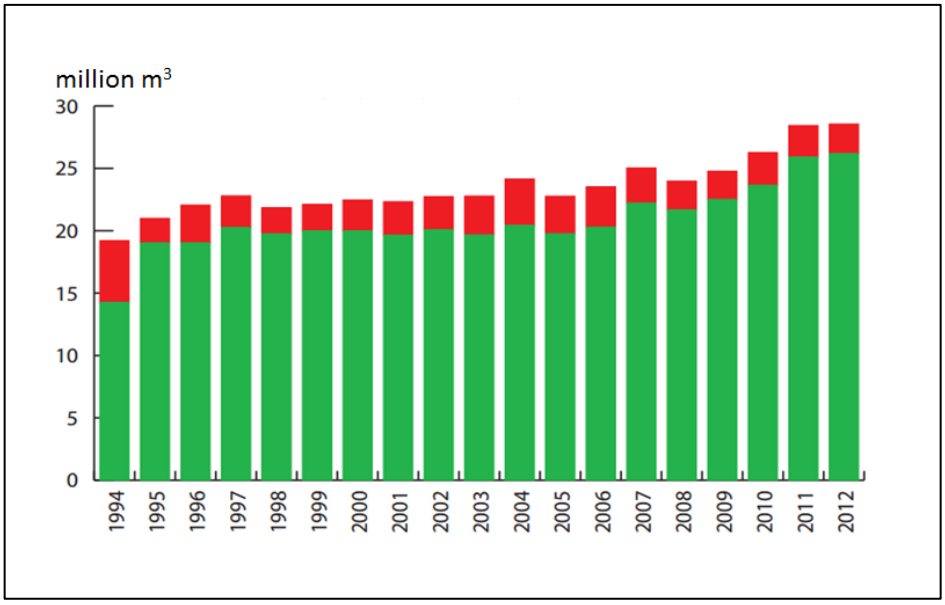

Figure 2.9 Biogas produced, in unit million m^3, in municipal wastewater treatment plants in Finland 1994 – 2012. Red (on top) indicates amount to flaring and green to utilization. Adapted from Huttunen & Kuittinen (2013).

According to Monnet (2003) AD treatment for industrial wastewaters was growing rapidly in the beginning of 2000's. Industries on such fields as chemical organics and food preparation produce wastewaters which could contain significantly higher organic loads than municipal and thus, the entire stream may be treated with AD (EPA, 2012). Concerning one of the largest industries in Finland, in pulp and paper factories anaerobic digestion is used as an inexpensive pretreatment method to control odors and reduce cost of final aerobic treatment of wastewaters (Monnet, 2003). As mentioned in Chapter 2.3, lignocelluloses are not directly suitable for proper biogas production due to strong compounds and micro structures.

2.4.4 Recovery of landfill gas

Landfill gas is generated in anaerobic decomposition process of biodegradable organic waste, which proceeds over decades due to slowly degrading elements, such as textiles and wood. Generally, the landfill gas contains 45 – 60 % of methane while the gas composition is highly dependent on the type and age of waste, and it may contain toxic compounds. In the recovery site, release of volatile gas is blocked with a layer of aggregate and the gas is sucked through extraction wells to, usually vertical, gas pipeline. (John & Singh, 2011)

The main benefits of landfill gas recovery are preventing transport of toxic gases, reduction of GHGs and gaining cheap energy (Al Seadi, et al., 2008). Amount of landfill gas produced in one year in Finland, which is presented in Figure 2.10, is more than combined biogas production of agricultural, co-digestion and wastewater plants (Huttunen & Kuittinen, 2013). It should be noted that a substantial share of landfill gas and thus of overall biogas is burned in flares due to lack of utilization appliances.

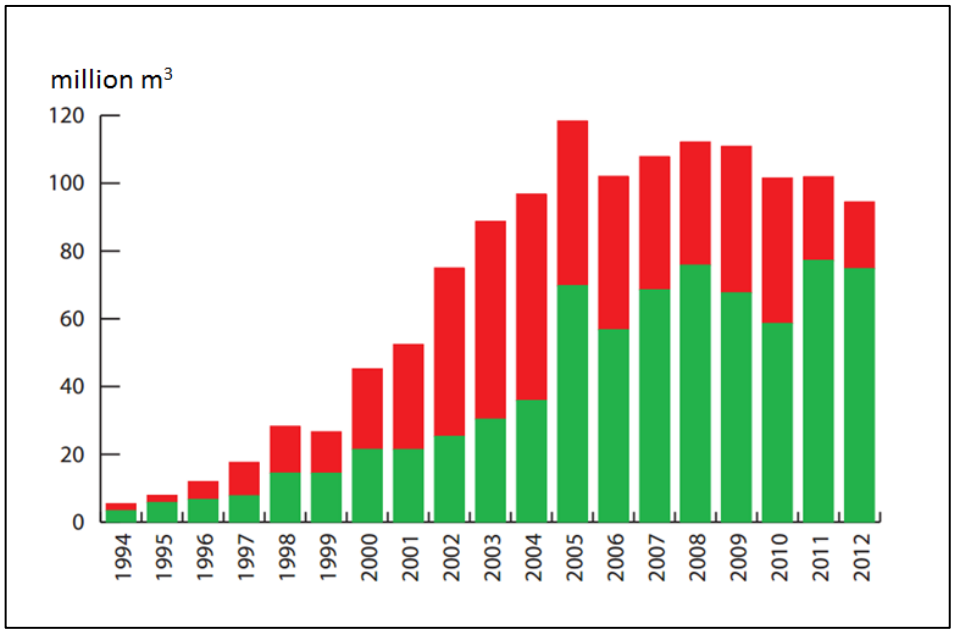

Figure 2.10 Landfill gas produced, in unit million m^3, in Finland 1994 – 2012. Red (on top) indicates amount to flaring and green to utilization. Adapted from Huttunen & Kuittinen (2013).

3 BIOGAS DIGESTATE

This Chapter concerns properties, processing and different utilization possibilities of fermentation residue, *digestate*, of biogas production based on recent scientific literature. The legislative issues are also set under the microscope since they are often essential factors on digestate applicability (Hahn & Hoffstede, 2010). The Chapter discusses digestate with emphasis on current status in Finland while applications, legislation and processes are studied in the Europe-wide scope. It should be noted that terminology on fertilization products is complex: in this study land applications of digestate are subcategorized under *fertilization products* as *fertilizers*, *soil improvers* and *growing media* according to the Finnish fertilizer regulation (539/2006). Also, denomination of sewage sludge generates difficulties as the matter is often called with the same name after the AD process, which is considered mainly as the stabilization method for the sludge.

One of the main benefits of anaerobic digestion is decrease in quantity of waste. Theoretically, the amount of solid and liquid organic residues can be reduced to 24 % whereas after aerobic degradation non-gaseous would account for 53 % of initial level (Schön cited by Deublein & Steinhauser (2011)), as presented in Figure 3.1. According to Al Seadi et al. (2008) the typical reduction value for AD at agricultural plant is 40 – 50 %. As reaching for optimum biogas process in terms of environment and economy, the amount of waste should be minimized and, thus, the digester residue should have a useful application as well. The sludge-like or liquid matter, digestate, contains water, residual carbon and the nutrients from the feedstock making it, for example, a potential fertilizer (Paavola, et al., 2009). (Al Seadi, et al., 2008).

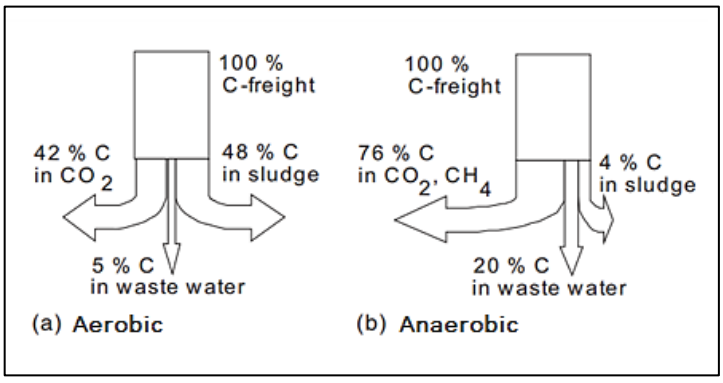

Figure 3.1 Flows of organic matter in aerobic (a) and anaerobic (b) degradation of biomass. Adapted from Deublein & Steinhauser (2011).

According to the EU terminology, digestate is "the semisolid or liquid product that has been sanitized and stabilized by a biological treatment process of which the last step is an anaerobic digestion step. It can be presented as whole digestate or separated in a liquor phase and a semisolid phase." The matter is considered a waste, while end-of-the-waste criteria are under definition in the EU (Saveyn & Eder, 2014). Average properties of raw digestate in Europe, according to study of about 1,800 samples, are presented in Table 3.1.

Majority of the AD plants feature wet process, and thus, water content of the digestate is high, typically 90 – 97 % (Hahn & Hoffstede, 2010). The matter is often first divided, e.g. mechanically in a centrifuge, into solid and liquid fractions to reduce volume and increase quality of the solid part in terms of handling and nutrient value. The liquid fraction can be processed further and utilized, which is common in agricultural biogas plants, or rejected as wastewater. The concentrated reject water requires purification, which is an existing process in wastewater treatment plants but in centralized plants requires additional measures. (Latvala, 2009) Also, commonly part of liquid digestate stream, and in some cases of solid stream, is re-fed back to the process to improve digestion efficiency (Al Seadi, et al., 2013b).

Table 3.1 Average properties of raw digestates in European analysis of around 1,800 samples performed 2009 – 2012 (EBA cited by Fachverband Biogas et al. (2013)).

Value	*DM (%)*	*ODM of DM (%)*	*pH*	*N of DM (%)*	*NH_4-N of DM (%)*	*P_2O_5 of DM (%)*	*K_2O of DM (%)*
Arithmetic average	5.7	69.3	7.9	10.4	6.0	3.8	5.3

3.1 Digestate in the waste hierarchy

Digestate is considered a waste in the Waste Framework Directive (2008/98/EC) of the European Parliament and of the Council, and thus, its treatment should base on the waste hierarchy of the EU, presented in Figure 3.2. The figure also includes examples of digestate uses on different levels. In context with waste management, fertilization is preferred over combustion: the solid substances of the digestate are recycled to benefit plant growth while in the combustion only the energy bound to organic compounds is recovered. Landfilling is the least favored option for digestate use.

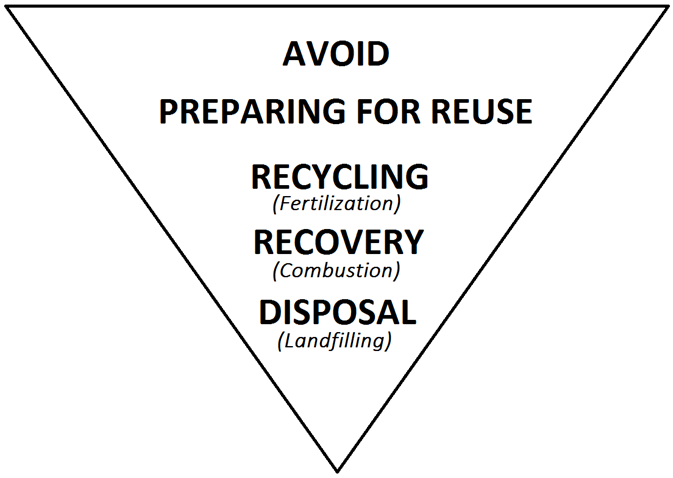

Figure 3.2 The waste hierarchy of EU's waste policy (2008/98/EC) and classification examples of digestate use.

3.2 Digestate markets

Overall, the digestate markets are undeveloped and the general knowledge of the applications is low (King, et al., 2013). The countries with advanced biogas sector, such as Germany, Denmark, Austria, Sweden, Switzerland and the UK, have also developed the digestate use furthest (Al Seadi, et al., 2013b). One of the leading digestate R&D organizations is British non-profit company WRAP (Waste and Resource Action Programme), who has defined the market sectors for digestate in summer 2012 in the study compiled by King & Bardos (2013). The sectors, unified with the Finnish fertilizer legislation, are presented in Table 3.2. Similarly, the general alternatives for digestate applications are, according to Jansen (2011), use as fertilizer, soil improver, growing medium, solid fuel or landfill matter. The digestate often provides a portion of the matter required in the application.

Table 3.2 Markets sectors of digestate applications based on report by King & Bardos (2013). First three sectors are unified with the Finnish fertilizer legislation (539/2006).

Application sector	***Description***
Agriculture	*Vegetable, fruit and crop production*
Soil manufacture	*Soil improving*
Growing media	*Container growing and landscaping*
Forestry	*Timber production*
Construction	*Wood substitute in fiber board*
Thermal treatment	*Thermal production of energy*

For their report *"Evidence for digestate use in different UK markets: an annotated bibliography"*, King & Bardos (2013) searched, analyzed and categorized literature sources concerning digestate applications. 37 % of the sources were written in the UK, 57 % elsewhere in Europe and 6 % in North America. The segmentation of the applications found is presented in Figure 3.3. Observing the market sectors, agriculture is clearly the most promoted field with share of 68 %. The second largest sector, land, which stands for unspecified land application, indicates small differences between the applications e.g. soil improvers and growing media. The similar requirements complicate the standardization work, and thus, multipurpose products are common terms for compost and digestate applications (Rigby & Smith, 2011). However, the EU report by Saveyn & Eder (2014) indicates even more intense focusing on agriculture: more than 95 % of the digestates produced in Europe are spread to agricultural land as liquid fertilizers and less than 3 % are processes to advanced products, e.g. growing media. (King & Bardos, 2013)

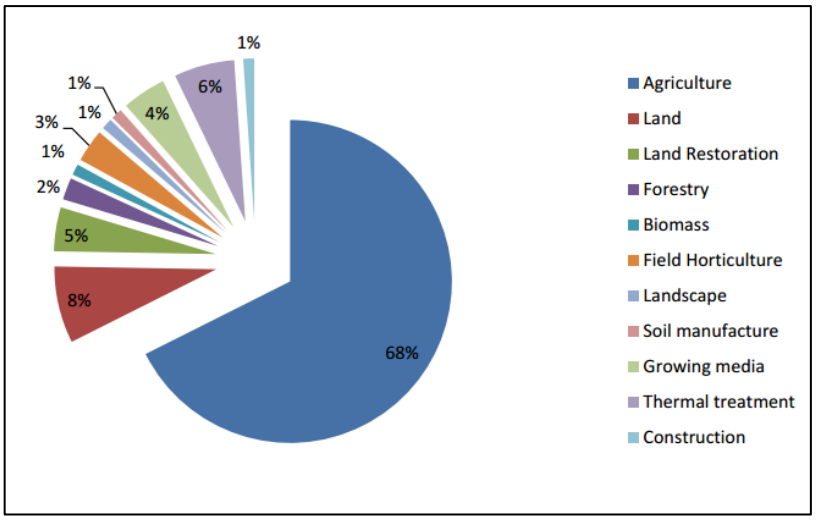

Figure 3.3 Division of bibliography sources on digestate use between different market sectors (King & Bardos, 2013).

According to Partanen (2010), there were no successful digestate products in Finnish market in 2010 due to lack of homogeneity of matter, knowledge and standardization. However, the growing biogas production, especially in agricultural and co-digestion plants, has promoted the product development. For example, corporations such as Lakeuden Etappi Oy (Tontti, et al., 2010) and Biovakka (Paavola, 2013), and a municipal water and waste treatment authority in Helsinki, HSY (Helsingin Seudun Ympäristöpalvelut,) (Wäänänen, 2011), have produced fertilization products since late 90's. Also noteworthy, Biotehdas Oy develops currently a market place for digestates in a Bioravinnepörssi-project (transl. bionutrient market) (Suvilampi, 2013).

EU countries often have characteristic digestate applications. In countries of Western and Central Europe, such as Germany, the digestate is often split to solid and liquid fractions, of which solid, the minor part, is composted and liquid, if not recycled in the process, is used directly in agricultural fertilization. As for Scandinavia, the digestate is typically spread to agricultural land as a whole. In Belgium, private utilization of digestate is strictly regulated while in the UK a quality protocol has been developed for AD to define end-of-waste criteria for digestate: eight treatment plants are producing certified products for public use. An annual digestate production in Europe is estimated to be 56 Mtonne fresh matters, of which 36.5 Mtonne accounts for Germany. (Saveyn & Eder, 2014)

3.3 Digestate applications and related characteristics

Use of digestate is dependent on its properties and the requirements of the usage conditions (Al Seadi, et al., 2013b). The properties vary broadly due to different substrates, pretreatment of those, the AD conditions and the post-processing. Factors such as nutrient and organic content, pH value, and content of contaminants and pathogens determine applicability of the digestate (Monnet, 2003) while usually the end product should also be easy to handle and of uniform quality. AD conditions and pretreatment of substrate have effect on pH value, pathogen removal and quality of

nutrients whereas the quantity of nutrients does not change during the digestion. (Marttinen, et al., 2013) When mapping different applications, the waste status has to be considered. Requirements of waste treatment have to be met when processing and applying the digestate and the side streams. The common applications of digestate include fertilizers, soil improvers, growing media, combustion and landfill (Jansen, 2011).

3.3.1 Land applications (fertilization products)

Using digestate for fertilization is usually considered the most favorable application due to content of organic matter and, especially, mineralized primary nutrients; nitrogen (N), phosphorous (P) and potassium (K) (Monnet, 2003). These promote substitution of inorganic fertilizers, which account for vast majority of the world fertilization use. Spreading digestate back to ground generates environmental benefit as the nutrient and carbon cycles are closed, as illustrated in Figure 3.4. (Lehtomäki, 2007).

In the AD process, part of the dry matter vanishes, viscosity of the substrate is reduced, the matter is homogenized and a major share of the organic nitrogen is converted to ammonium (Luostarinen, 2013). Thus, the digestate penetrates more easily to soil, causes less stress for soil organisms and availability of nitrogen to plants is enhanced compared to e.g. untreated manure. In addition, the immediate mixing to soil causes less odor problems and ammonia loss. Study by Tambone et al. (2010) proves high fertilization quality of digestate compared to the traditional organic soil improver, compost, while the soil amendment qualities are equal. (Hahn & Hoffstede, 2010)

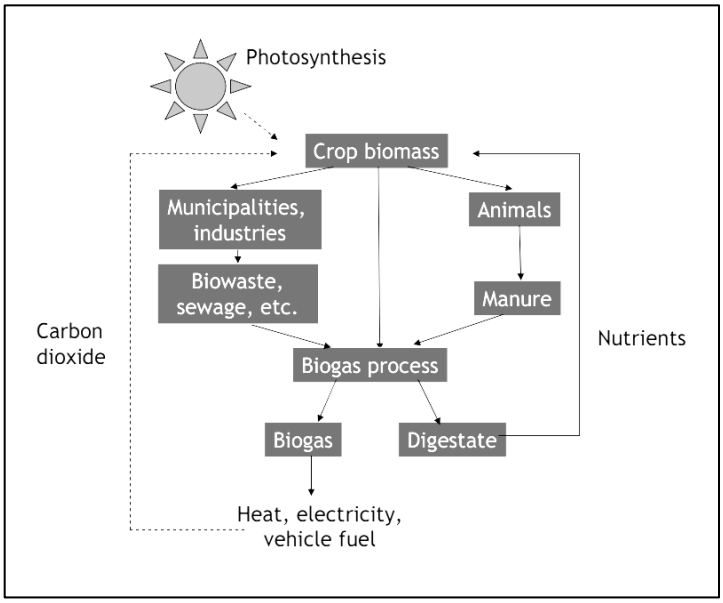

Figure 3.4 Carbon and nutrient cycles in the biogas process and land application of the digestate (Lehtomäki, 2007).

Since digestate is a by-product, the manageability of its properties is highly limited. Yet, the production process of digestate should be monitored and controlled continuously from substrate to final product to ensure the competitiveness versus

synthetic products. Content of nutrients and absence of impurities, such as pathogens, persistent organic pollutants and plastics, should be confirmed to assure safety and efficiency of fertilization. (Al Seadi & Lukehurst, 2012) For example, the nitrogen concentration of the digestate is highly variable depending on the substrate, as seen in Figure 3.5, and the digestion conditions (Fuchs & Drosg, 2013). According to Al Seadi and Lukehurst (2012), in Denmark the large centralized biogas plants feature a small laboratory for analysis of digestate quality.

The fertilization products of digestate origin, as categorized in Finnish fertilization regulation (539/2006), are fertilizers, soil improvers and growing media. Fertilization products can be produced at any type of biogas plants. Agricultural and co-digestion biogas plants generally promote fertilizer use while digestate from WWTP is typically used as soil improver or growing medium (Latvala, 2009). If digestate derives from sewage sludge, it is not suitable for all plants (Vuorinen, et al., 2013). Also, a European trend is use of digestate from wet fermentation, featuring majority of the biogas plants, completely in agricultural fertilization and from dry fermentation in compost with bio and green waste. Despite emerging upgraded products, e.g. for home gardens, 80 – 95 % of produced digestates in European countries are applied in agriculture. (Saveyn & Eder, 2014)

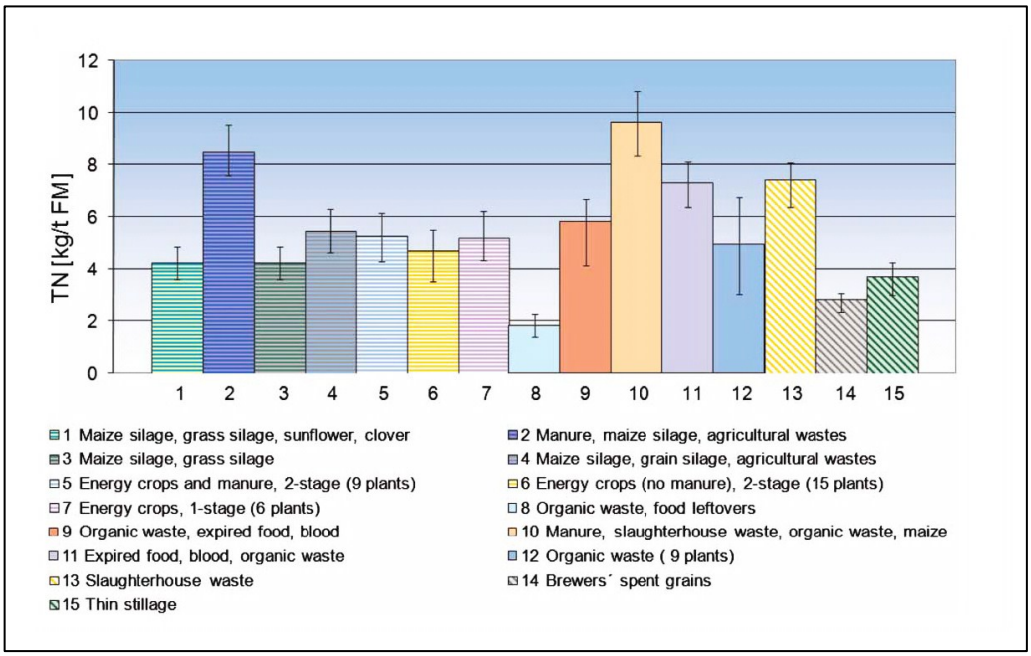

Figure 3.5 Nitrogen concentrations (TN) in digestates from different substrate mixes. Adapted from Fuchs & Drosg (2013).

According to Al Seadi and Lukehurst (2012) any land use of sewage sludge and sludge derived products is banned in some countries, for example the Netherlands, due to risk of chemical contamination. However, in e.g. the UK, Norway (ISWA Working Group, 2013) and Finland (Marttinen, et al., 2013) utilization of sewage sludge in fertilization is common. In the UK, 80 % of digested sewage sludge (King, et al., 2013) and in Norway 60 % of treated (incl. other stabilization processes) sewage sludge is utilized in agriculture (ISWA Working Group, 2013).

3.3.1.1 Fertilizer

According to study by Spaey et al. (2012) on clarifying fertilizer legislation in EU, organic fertilizer is *"material of plant or animal origin used to maintain or improve plant nutrition and the physical, chemical and biological properties of soil"*. The most common application for digestate is use as a fertilizer due to simple and profitable substitution of inorganic fertilizers and lowered environmental impacts (Al Seadi, et al., 2008). Especially agricultural biogas plants promote utilization of digestates at nearby fields (Fuchs & Drosg, 2013). The location also reduces need of dewatering or solid-liquid separation, which is often applied in centralized plants due to increased handling and spreading costs of high water content digestate (Hahn & Hoffstede, 2010).

Due to top fertilization quality of digestate among organic fertilizers, the ideal candidates for digestate use are organic farmers, who do not utilize inorganic fertilizers. The principle of fertilization in organic farming is to achieve natural nutrient cycle, and only fertilization products compatible with rules of organic farming may be used: for example, digestates originating from industrial animal breeding are banned (EC No 889/2008). Due to possibility of negative environmental impact, the digestate quality has to be assured. (Clements, et al., 2012) The nutrient value of digestate is higher than of compost, the traditional organic fertilizer, while the soil amendment value is similar (Tambone, et al., 2010). These days, several local fertilization products of digestate origin are available in Finland. Käytännön maamies, a Finnish magazine for agricultural entrepreneurs, has listed (Table 3.3) properties of organic fertilizers available in Finland, which may also serve as soil conditioners and growing media (Käytännön maamies, 2012).

Table 3.3 Selected Finnish organic fertilization products of digestate origin suitable for agricultural use. (Käytännön maamies, 2012) (MTT, 2012)

Producer	***Product***	***Type***	***Water (%)***	***ODM (% of DM)***	***pH***	***N Soluble (g/kg)***	***P Soluble (g/kg)***
HSY	*Metsäpirtin Maanparannuskomposti*	*Composted mixture of digestate and peat*	60	55	7.0	6.0	0.3
Biovakka	*Biovakka Humusvoima, Vehmaa*	*Digestate*	-	24	-	2.0	0.1
Biovakka	*Biovakka Moniravinne*	*Liquid digestate*	-	52	-	4.8 kg/m^3	0.4 kg/m^3
Biokymppi	*Luomukymppi A*	*Liquid digestate*	99	59	8.6	2.8	0.1
Biokymppi	*Luomukymppi B*	*Dried digestate*	75	85	8.4	1.0	0.0
Envor Biotech	*Peltoravinne*	*Digestate*	70	57	8.0	0.8	0.0
Lakeuden Etappi	*Maanparannusrae*	*Granulated digestate*	12	48	-	3.2 kg/m^3	0.1 kg/m^3

Fertilizers for agricultural use are also produced at co-digestion plants, advantages of which are large capacity, regular supply of substrates and rise in biogas yield of

manures and slurries as a result of mixing. Increased treatment volume allows more processing, but on the other hand, variable substrates also require e.g. more intense impurity removal and monitoring. (Paavola, et al., 2009) Co-digestion plants are most often built at central locations, which results in longer transportation distances, and thus, requirement of dewatering of the digestate. The digestate can be divided into several fertilizer streams. In large agricultural plants but especially in co-digestion plants, the digestate is first split into phosphorous rich solid fraction and nitrogen rich fluid fraction. (Hahn & Hoffstede, 2010) This refers to *partial conditioning*, while in *complete conditioning* the digestate is separated further in three fractions: pure water, concentrated nutrients and organic fibers (Al Seadi, et al., 2008). Different digestate streams are applicable to different fertilization necessities (Marttinen, et al., 2013) and adjustment of nutrient ratios by mixing. (Al Seadi & Lukehurst, 2012)

Compared to fertilization value of untreated manure or slurry, anaerobic digestion increases nutrient value, removes pathogens and homogenizes the matter (Al Seadi, et al., 2008). Ammonium content is increased by 20 – 30 % and, consequently, the need of inorganic N-fertilizer is reduced by 20 – 30 %. The content of phosphorous remains approximately the same while in Finland most of the dairy farms use additional phosphorous only in cattle feed. Also, the organic, soil improving substances in digestate are beneficial for agricultural fields: use of synthetic fertilizers reduces content of humus, which can be increased with organic fertilizers (Partanen, 2010). To decrease negative environmental impacts of infiltration, e.g. eutrophication, the crop nutrient requirement should match with the content of digestate: The phosphorous in digestate is usually the limiting factor in agricultural use, and thus, inorganic nitrogen is required as a complement. Appropriate application time and proper storage prevent nutrient leaching. (Lukehurst, et al., 2010) (Paavola, et al., 2009)

3.3.1.2 Soil Improver and growing medium

According to CEN (European Committee for Standardization) standard CR 13456:1999 on soil improvers and growing media, cited by Teglia et al. (2011), *soil improver* (a.k.a. soil amendment and soil conditioner) is material that is *"added to the soil in situ primarily to maintain or improve its physical properties, and which may improve its chemical and/or biological properties or activity"*. The main purpose of a soil improver is to add nutrients and humic substances to soil, and thus, upgrade the environment for plant roots. The organic matter share of dry matter in digestate varies roughly between 40 to 85 %. (Teglia, et al., 2011) The soil improvers are used e.g. in land restoration, landscaping and horticulture (King, et al., 2013).

Growing medium stands for "*material, other than soil in situ, in which plants are grown"* (CEN standard CR 13456:1999 cited by Teglia et al. (2011)). Growing medium is often a mixture of organic substance and mineral soil e.g. peat and fine sand. Also, depending on the usage, inorganic fertilizers and lime can be added to the media. Common application of growing media is landscaping: building of lawns, scrublands and parks as well as finishing closures of landfills. (Myllymaa, et al., 2008a) For production of horticultural crops in containers the organic content of growing medium is 100 % (Restrepo, et al., 2013), for lawn building around 50 %, for park building around 40 % and for sport fields around 10 to 20 % (Helander cited by

Myllymaa et al. (2008a)). Peat, wood chips and composted biowaste are common organic materials in growing media, which can be substituted with digestates. Recently, usage of peat has been questioned due to environmental concern on its slow regeneration rate and high carbon content (Restrepo, et al., 2013).

Requirements for the soil improvers and the organic part of growing media are similar: mainly to provide nutrients and humic substances in order to improve soil quality and plant growth (King, et al., 2013). Thus, in English literature, multi-purpose products are common terms for such applications, which also may serve as fertilizers (Rigby & Smith, 2011). Multifunctional *soil improver-growing media (SIGM)* is commonly produced from the solid fraction of digestate by composting. In composting, the organic compounds decompose aerobically into humus ensuring stability, and more nitrogen is mineralized (Frischmann, 2012). As a result, the digestate is turned into high quality compost, which increases microorganisms, nutrients, water retention capacity and pH buffer capacity of the soil (Saveyn & Eder, 2014). Compared to composting alone, the combination of digestion and composting generates higher environmental value mainly due to biogas production (Myllymaa, et al., 2008b), while the digestate most often requires mixed compost due to lack of organic matter (Al Seadi, et al., 2013b).

The main difference between uses of SI-GM and fertilizer is frequency of soil cultivation: the fertilizers are spread seasonally. Similarly to fertilizers, infiltration of nutrients may occur with soil improvers and growing media, yet, the threshold values are considered to be broader. Often, the more processed, e.g. composted, the digestate is, the more suitable it is for soil improving or bedding rather than plain fertilization (Partanen, 2010) According to a desktop study by Rigby & Smith (2011), for use in horticulture, the digestate should be supplemented with extra P and K to reach level of home garden fertilizers while in use as mushroom growing media, the digestate may have potential. (Al Seadi, et al., 2013b).

In England, Terra Ecosystems has successfully merchandized soil improvers and growing media of sewage sludge digestate origin from early 90's (Evans, 2009) while in Finland, few companies started production in the late 90's (Tontti, et al., 2010) (Wäänänen, 2011). Today, around 10 certified operators produce fertilization products from digestate (Evira, 2013a). In addition to agriculture, horticulture and public green zones, the soil improvers and growing media can be utilized in forestry fertilization after granulation (Partanen, 2010). However, the transportation distances and processing increase costs, and thus, the success in forestry is unlikely.

3.3.2 Combustion

According to the waste hierarchy of the EU (2008/98/EC), shown in the Figure 3.2, utilization of digestate through recycling, e.g. as a fertilizer product, is always more favorable than combustion (i.e. energy recovery). However, in some cases, e.g. if appropriate sanitation level cannot be reached or due to lack of agricultural land (Al Seadi, et al., 2013b), the matter should be combusted rather than landfilled (i.e. disposal). In the most EU states, e.g. in Denmark from 1997 and in Sweden from 2002, the landfilling of organic matter has been banned (Blumenthal, 2011). In Finland, total ban has not been enacted but all wastes shall be treated rather than landfilled

(Braun & Wellinger, 2003). On years 2004 – 2008 landfilling accounted for 1 – 3 % of sewage sludge placement (Häkkinen & Merilehto, 2012).

The benefits of combustion are reduction of organic matter, complete sanitation, energy recovery (Hahn & Hoffstede, 2010) and possibility utilize nutrients, mainly phosphorous, in the ash, e.g. with *ASH DEC* technology (Havukainen, et al., 2012). However, in Finland the act on fertilizer products regulates only ash from wood, peat and field biomass to be used as fertilizer, and thus, e.g. ash from wastewater digestate is not usable (539/2006). Downsides of combustion include high energy intensity of drying, ash disposal and NO_x emissions due to high nitrogen content (Fuchs & Drosg, 2013).

In current definitions and standards, digestate is not classified as a biofuel (Kratzeisen, et al., 2010), though it could be applied equally: co-combusted e.g. with coal, or combusted as a single fuel (Hahn & Hoffstede, 2010). The digestates are considered wastes (2008/98/EC), and thus, may mainly be combusted in an incineration plant or a co-incineration plant. Exceptions are sludge origin digestate from wood industry combusted at integrated plant and plant origin digestate from agriculture or forestry (151/2013). Co-incineration is applied in fluidized-bed boilers and grate boilers. (Hupponen, et al., 2012) The digestate can be dried thermally to dry matter content of 90 % and pelletized reaching lower heating value of 10.5 MJ/kg (Partanen, 2010). Thus, it may be used similarly to milled peat (DM 46-48 %, 9.6 MJ/kg (Alakangas, 2000)). On the other hand, in context of energy use the digestate could serve as a feedstock for biofuel production (Frischmann, 2012).

Kratzeisen et al. (2010) studied combustion of two different digestates, which were dried with waste heat of a power plant and pelletized resulting in LHV of 15.0 – 15.8 MJ/kg (comparable to wood), water content of 9.2 – 9.9 %, and fuel gas emissions within biofuel limits. The waste heat covered 90 % of process energy and thus, the production cost and overall price of the digestate pellets were low making it a recommended alternative fuel. Other observations were the high ash content (15 – 20 %) and odor emissions, why the digestate should be combusted near to the AD facility. Also, as for fertilization products, the variability of digestate properties may affect the applicability. (Kratzeisen, et al., 2010) In Finland, dried wastewater digestate has been co-combusted as secondary fuel at least in Haapavesi by Vapo Oy (Hupponen, et al., 2012).

3.3.3 Other applications

In addition to the discussed main applications, few other alternatives have been considered to have potential. WRAP report by Rigby & Smith (2011) investigates new markets for digestates: use as construction material, algal culture and feedstock for biofuel production are determined to be promising applications. Technology featuring production of separate nutrient pellets for fertilization and fuel pellets for combustion, developed by *GG Eco solutions*, is assessed as an existing but development requiring technology. However, in the report, the information on the last mentioned is from personal communication and little data seems to be available e.g. at http://www.ggecosolutions.com. Another feasible application for dried digestate is animal bedding (Al Seadi, et al., 2013b).

3.3.3.1 Fiberboard and composite

In the field of construction, the digestate can be used as a fiber source for e.g. medium density fiberboards (MDFs) or wood-plastic composites (WPCs) substituting wood. Matuana & Gould (2006) compared properties of fiberboards and fiber-plastics produced using daily manure digestate to traditional materials; pine and maple. The bending strength, stiffness and internal strength of digestate origin material was equal or exceeded standard values. According to Spelter et al. (2008) particleboard of digestate origin may have economic potential, while there are several problematics to overcome, e.g. requirement of large volume and constant supply of homogenous matter to manufacturer.

3.3.3.2 Algal culture and ethanol production

Cultivated algae fed with nutrients of organic biomass, e.g. digestate, may serve for many purposes: as a slow release fertilizer due to extracted nutrients (Wilkie & Mulbry, 2002), as an animal feed due to high protein content or as a feedstock for biofuel production, for example through AD process. Thus, algae cultivation could show potential especially in agricultural biogas plants. (Rigby & Smith, 2011) The digestate can also be used directly as a biofuel source: the long-chain organic compounds, such as cellulose and hemicellulose, which do not disintegrate in the AD process, may serve as source of sugar required in bioethanol production. According to study by Michigan State University (Yue, et al., 2010) (Teater, et al., 2011) ethanol conversion yield of dairy manure digestate was slightly higher than of switch grass or corn stover, which are common sources for cellulosic ethanol. An ethanol production per tonne of cattle manure was calculated to be 41 kg. However, for both algae and ethanol production, further research and experiences are required to increase knowledge of the feedstock, process and post-processing requirements (Rigby & Smith, 2011).

3.4 Legislation concerning digestate use

In the EU, numerous regulations control usability of digestate in terms of sanitation and emissions. Animal by-product regulation concerns AD substrate usability, waste laws define criteria and treatment options for wastes while each digestate application is additionally regulated with a specific legislation. The aim of the legislative framework is to increase and ensure usability of digestate by managing hygienic and environmental issues (Saveyn & Eder, 2014).

3.4.1 Animal by-product regulation

Regulation on the use of animal by-products (EC No 1069/2009) defines rules, and regulation 142/2011 (EU No 142/2011) the hygienization requirements for treatment, utilization and disposal of animal origin by-products, which are not intended for human consumption. As shown previously in Table 2.2, such by-products include e.g. manure, slaughterhouse waste and catering waste. The ABPR is often mentioned as the essential statute on biogas production and digestate use. The by-products are divided in three categories dependent on the level of hygienic risk, see Table 3.4. If the matter contains mixture of different categories' by-products, it should be treated as the material from the lowest category. Other treatment

processes, e.g. chemical hygienization, drying, combustion and post-composting, may also be approved if they are verified by the competent authority during the facility validation. (EU No 142/2011)

In Finland, the competent authority operating supervision and authorization of biogas plants is food safety authority Evira. Sewage sludge and the materials which do not require pretreatment in regulation 142/2011 should be digested in thermophilic conditions: for two weeks in 55 °C temperature. If manure is treated at an own AD facility of the farm or farmer community, neither authorization of the plant nor hygienization is required. When manure is not pretreated, the raw digestate is hygienically considered as untreated manure. (Pelkonen, 2013)

Table 3.4 Categorization of animal by-products according to regulation EC No 1069/2009 and required treatment methods (EU No 142/2011). Differing treatment methods of various temperature levels and retention times for different particle sizes are also mentioned in the regulation EU No 142/2011.

By-product category	***Description***	***Material***	***Minimum treatment requirements for AD***
Category 1	*Material with highest health and environmental risk*	*Any body parts of animals suspected of being infected by TSE or a communicable disease*	*Only products deriving from processing of category 1 material suitable for AD*
Category 2	*Epidemic (not TSE) risk materials, and those exceeding safe levels in contaminants*	*Manure, digestive tract content, milk and colostrum*	*No treatment required*
		Other category 2 material	*Pressure sterilization at 133 °C and 3 bar for 20 min, particle size ≤ 50 mm*
Category 3	*Material without sign of communicable disease or fit for human consumption but not intended for it*	*Deteriorated food and feed products (not from international transport)*	*No treatment required*
		Other category 3 material	*Hygienization at 70 °C for 60 min, particle size ≤ 12 mm*

3.4.2 Fertilization legislation

Currently the EU regulation on fertilizers (EC No 2003/2003) concerns only inorganic fertilizers and is therefore mainly irrelevant for digestates. However, urge for including organic fertilizers in the main fertilizer regulation has been noted by the European Commission and the harmonization options are reported by Spaey et al. (2012). Organic fertilizers are considered in the EU regulation on organic farming whilst it should be noted that some digestate fertilizers, e.g. of industrial animal breeding origin, are not suitable for organic farming (EC No 834/2007) (EC No 889/2008). Soil improvers and growing media are defined in CEN standards by the standardization committee CEN/TC 223. According to CR 13456:1999, the minimum organic content of digestate used as soil improver is, dependent on the product, from 20 to 90 % of the dry matter while also national legislations are variable (Teglia, et al., 2011).

The national act on fertilizer products in Finland covers also products of digestate origin. The act can be considered as the main regulator on digestates, which are not covered by animal by-product regulation, such as sewage sludge and plant residues (Marttinen, et al., 2013). The fertilization products include fertilizers, liming materials, soil amendments, growing medium, microbe products and untreated by-product fertilizers. (539/2006) The requirements for fertilizer products are specifically defined in the national type designation list (Evira, 2013b) operated by Evira, which bases on the decree of the Ministry of Agriculture and Forestry on fertilizer products (24/11 Appendices I-IV). The designations, under which digestate products can be set, and descriptions are seen in Table 3.5. (Vuorinen, et al., 2013) The decree on fertilizer products also assigns by-products from root vegetable and municipal biowaste to be treated thermally in 70 °C for one hour (Marttinen, et al., 2013).

Table 3.5 Designations for digestate products in the Finnish national type designation list. Adapted from Evira (2013b).

Designation	***Designation group***	***AD related product description***	***Application***
Digestate	*By-products for soil improvement as such*	*Hygienic residue of mesophilic or thermophilic AD as such or mechanically dewatered*	*Fertilizer, soil improver* [I]
Fresh compost	*Organic soil improvers*	*Post-composted AD residue, required stability*	*Fertilizer, soil improver, growing medium, corrosion prevention*
Soil improver compost	*Organic soil improvers*	*Post-composted AD residue, required maturity*	*Soil improver, corrosion prevention*
Manure mixture	*Organic soil improvers*	*AD residue of manure and/or litter origin, may be composted and mixed to compost improver*	*Fertilizer, soil improver*
Reject water	*By-products for organic fertilization as such*	*Liquid by-product from AD residue, suitable for organic fertilization*	*Fertilizer*
Dry grain or powder	*Organic soil improvers*	*Thermally or correspondingly treated or granulated AD residue*	*Fertilizer, soil improver, growing medium*

I *If the product includes residue from sewage sludge, it should be described as unsuitable for production of fresh vegetables, herbs, seedlings and for home gardens.*

The European Nitrate Directive (91/676/EEC) controls excessive nitrate use in agriculture, covering also digestate usage, in order to protect ground and surface waters. The nutrient content and application time of digestate should match the nutrient demand of plants. If digestate is applied into land when plant uptake is low, the nutrients might leach into ground and surface waters. (Lukehurst, et al., 2010) When digestate, produced from sewage sludge, is intended for agricultural use, the European Council directive on sewage sludge use in agriculture (86/278/EEC) should be taken into account. The aim of the directive is to encourage for sewage sludge utilization in agriculture while control content of harmful substances to prevent negative impacts on environment.

3.4.3 Waste legislation

Digestate is considered a waste in the Waste Framework Directive (2008/98/EC) of the European Parliament and of the Council. However, mainly due to fertilization and soil amendment properties, digestate is further qualified as underused material (EC, 2010b) and work on defining end-of-waste criteria has been started. According to the end-of-waste principle, the waste ceases to be a waste if it can be considered a product in the market. Such criteria have already been enacted in the UK whereas in the Czech Republic, digestate may be specified as a product by other national regulations. Most of the EU states have no specific end-of-waste legislation for digestate but it may obtain a product status by e.g. fertilizer legislation. (Saveyn & Eder, 2014)

In any case, the national waste legislations, following the EU directive, define unprocessed digestate as a waste. In Finland, The Government Decree on Waste (179/2012) instructs different treatment methods for wastes, which follow the waste hierarchy (Figure 3.2) defined in the EU's waste policy: recycling of the matter is always preferred over recovery, i.e. combustion to produce energy, while disposal is the least favored option. In Finland, Decree on Waste Incineration (151/2013) controls combustion of digestate while landfilling of digestate is concerned by The Government Decree on Landfills (331/2013), which was enacted in 2013 in order to inhibit landfilling of material with organic content more than 10 %.

3.4.3.1 Waste incineration

As digestate is considered a waste (2008/98/EC), its combustion should be called incineration, which takes place in an incineration or co-incineration plant (Hupponen, et al., 2012). Exceptions are sludge origin digestate from wood industry combusted at integrated co-combustion plant and single combusted plant origin digestate from agriculture or forestry (151/2013). The EU directive on waste incineration (2000/76/EC) defines conditions and requirements for waste incineration and co-incineration plants treating more than 50 tonne combustible waste a year. In Finland, the EU directive is followed by the Government Decree on Waste Incineration (151/2013). The digestate may achieve standardized status of *waste derived fuel,* or further *solid recovered fuel,* if the matter meets tighter quality requirements of EN 15359:2011 (King, et al., 2013).

Waste incineration is also concerned in the industrial emission directive (IED) (2010/75/EU), which covers all noteworthy industrial processes causing potential environmental impact. The directive obligates the member states to actualize the best available technologies (BAT), which are adopted via multi-phase process coordinated by IPCC Bureau, in practice. In addition to specific technologies and process conditions, the current BAT paper on waste incineration (EC, 2006b) includes energy efficiency, emission limits and noise limits. Also, limits for maximum emissions in waste incineration, which cannot be exceeded in any case, are defined in the appendix VI of the IED directive. Review of new BAT conclusions is estimated to start in 2014. In addition to BAT of waste incineration, BAT paper on waste treatment industries (EC, 2006a) touches on the digestate as it covers emissions from anaerobic digestion.

4 DIGESTATE PROCESSING

This Chapter contains the main theory of different digestate treatment processes, which aim to improve quality of the matter. The literature covers mainly digestate processing for agriculture (Crolla, et al., 2013) and in few cases, for combustion (Hupponen, et al., 2012). The WRAP report *Enhancement and treatment of digestates from anaerobic digestion* (Frischmann, 2012) is the most extensive source of background information found as it covers all common processes and also the latest technological proceedings. The general processing paths for digestate are seen in Figure 4.1 (Williams & Esteves, 2011)

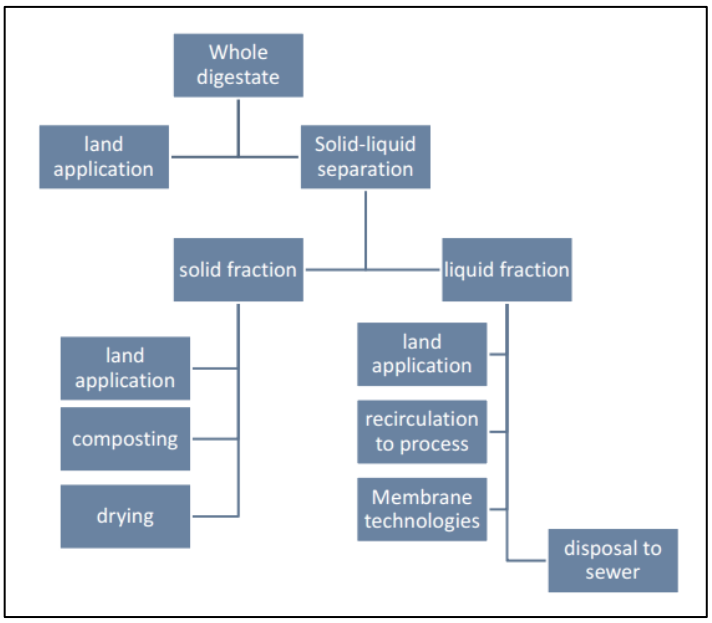

Figure 4.1 Common processing alternatives for the digestates. Adapted from Williams & Esteves (2011).

For fertilization applications, the main objectives for digestate processing are reduction of volume due to high water content, recovery of nutrients and securing environmental safety. These are pursued through two general processing concepts: partial conditioning and complete conditioning. (Hahn & Hoffstede, 2010) Partial treatment aims mainly for volume reduction in order to lower treatment and transportation costs by splitting the matter into two fractions, liquid and solid, with simple technology. The solid fraction may be utilized directly as fertilizer or composted while fluid may as well serve as fertilizer or be re-fed back to the digester. In complete conditioning, the matter is separated further into purified water, solid fibers and nutrients through more energy intense and expensive process. For use as soil improver or growing medium, dry fraction of the digestate is usually composted to improve its humus content and stability. (Al Seadi, et al., 2013b)

In order to utilize digestate in energy production, the matter should be dried. For combustion, the dry matter content should be at least 40 – 60 % (Latvala, 2009) while stability is ensured, heating value enhanced and molding in storage prevented by dry matter content of 85 – 90 %. To achieve these levels, the digestate should be dried

thermally. (Hupponen, et al., 2012) Before thermal drying, the DM content is often raised to around 30 % in mechanical drying. (Latvala, 2009) As observed, different dewatering methods are the main procedures in digestate processing. Due to low value of the matter, cheap processing is generally essential as the relative value increase in conditioning is often low as well (Fuchs & Drosg, 2013). Examples of different processing technologies for enhancing value of digestates are presented in Table 4.1 while more processes and possible chains for those are illustrated in a flow chart in Appendix 1 (Frischmann, 2012). Also noteworthy, hygienization may be applied to the matter alternatively after digestion (Pöyry Environment Oy, 2007).

Table 4.1 Examples of different physical, thermal, biological and chemical processing technologies. Adapted from Frischmann (2012).

Physical	***Thermal***	***Biological***	***Chemical***
Screw press (dewatering)	*Rotary dryer*	*Composting*	*Ammonia stripping*
Centrifuge (dewatering)	*Belt dryer*	*Algae production*	*Membrane contactor (nutrient recovery)*
Hydrocell (dewatering)	*Surface heat exchangers (evaporation)*	*Ethanol production (hydrolysis)*	*Ion exchange (nutrient recovery)*
Electrokinetics (dewatering)	*Conversion (Incineration)*	*Microbial Fuel Cell*	*Acidification*
Ultrafiltration (purification)	*Conversion (Gasification)*	*Biological Oxidation*	*Alkaline Stabilization*

4.1 Hygienization

Main regulator in the EU for the *hygienization* of digestate is the animal by-product regulation (EU No 142/2011), which is discussed further in Section 3.4.1. Generally, requirements for hygienic treatment include sufficient particle size, temperature level and retention time. As for substrates not covered by animal by-product regulation, such as sewage sludge and plant residues, the fertilizer legislation (539/2006) determines required properties and processing. In Finnish study including three different hygienization processes by Marttinen et al. (2013), the pathogen contents of digestates were generally clearly below critical levels. Sanitation process may be applied to the digested matter before or after the biogas production. In pretreatment, the aim is also to enhance the degradability of organic compounds: as a result, biogas generation is improved and digestate becomes easier to dewater (Luostarinen, et al., 2011).

In addition to pure heating, thermal hygienization processes include e.g. thermal hydrolysis process (THP), autoclave systems and enzymic liquefaction (Frischmann, 2012). However, an alternative hygienization process may as well be used when accepted by a validation procedure or nationally approved (Marttinen, et al., 2013). Such processes could be drying, composting or chemical treatment, e.g. *alkaline stabilization* or *acid-peroxide conditioning* (Pöyry Environment Oy, 2007). Also, these

are often applied to digestate of sewage sludge origin to ensure its stability and sanitation. In calculations of this study, the alternative sanitation is achieved by chemical treatment of whole digestate, as the other main options, drying and composting, are applied only to solid fraction. Due to low energy demand of chemical production, chemical pasteurization may generate energy savings, which are, however, doubtful due to possible increase of methane production in thermal pretreatment. Also, the sanitation efficiency is uncertain for differing AD substrates, as the process is studied mainly for sewage sludge.

KemiCond process is an example of acid-peroxide conditioning, in which the matter is simultaneously pasteurized and flocculated by acidification and oxidizing. Firstly, the digestate, is treated with sulphuric acid to decrease the pH to around 4, broke the gel structure and dissolve iron as ferrous. Next, hydrogen peroxide is added to pasteurize the matter and oxidize ferrous ions, which leads to co-precipitation of phosphorous and organics. The micro-flocculation results in improved separation of phosphorous and organics in mechanical separation. (Thunberg, 2010) In the common alkaline stabilization, lime treatment, *burnt lime (CaO)* or *slaked lime ($Ca(OH)_2$)* is added to raise pH of treated matter over 12 and temperature to 50 – 70 °C in order to achieve pasteurization and stabilization. (Vuorinen, et al., 2013) Since energy consumption of chemical production for KemiCond process is lower, as seen in Table 4.2, it is used in the calculations of this study.

Table 4.2 Energy consumption comparison of chemical productions for lime stabilization and KemiCond.

Feature	***Unit***	***Lime stabilization***	***KemiCond***
Chemical consumption	$g/kg\ DM_{digestate}$	CaO 600[I]	*Sulphuric acid* 234[II] *Hydrogen peroxide* 27
Energy consumption	$kWh/kg\ DM_{digestate}$	0.58[III]	0.09[IV]

I (Vuorinen, et al., 2013)
II (Thunberg, 2010)
III *Energy consumption of burnt lime production: 0.97 kWh kg^{-1}* (Pohjois-Suomen Ympäristölupavirasto, 2006).
IV *Energy consumption of sulphuric acid production: 0.077 kWh kg^{-1}* (AVI, 2011) *and of hydrogen peroxide: 2.6 kWh kg^{-1}* (Kaakkois-Suomen Ympäristökeskus, 2005).

4.2 Solid-liquid separation

Due to high water content, the digestate is most often dewatered to ease handling and transportation. Also, as the matter is split in *solid-liquid separation*, two separate fertilizer streams of differing nutrient properties are gained (Al Seadi, et al., 2013b). Usually, the nitrogen rich liquid fraction is applied as a fertilizer, recycled back to the process or purified while solid fraction is used in land application, composted or dried further (Saveyn & Eder, 2014). After mechanical separation, the DM content of phosphorous rich solid fraction is around 10 to 30 % and may be raised to over 90 % in thermal drying (Latvala, 2009). Average division of the main constituents in digestates processed with screw extractors and rotary screen separators is presented in Figure 4.2.

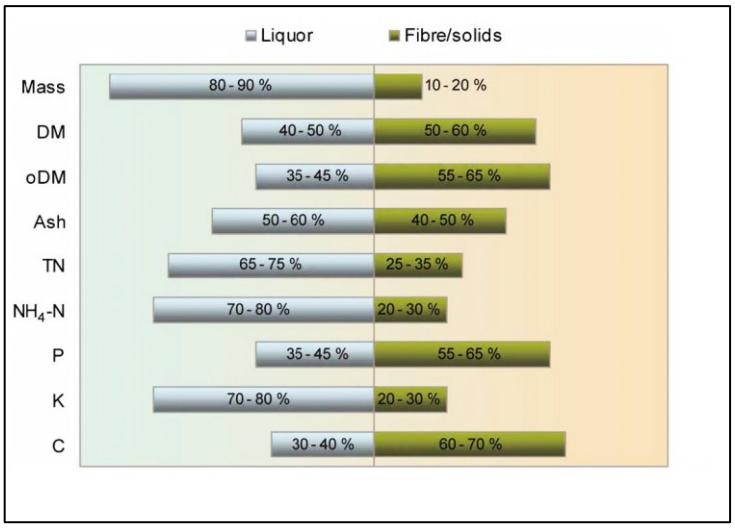

Figure 4.2 Division of the main elements in solid-liquid separation. Bauer et al. (2009) cited by Fuchs & Drosg (2013).

Mechanical separation is currently the essential procedure in digestate processing (Saveyn & Eder, 2014). In order to achieve proper manageability for the solid fraction, the DM content should be more than 25 % (Lebuf, et al., 2012). The most popular separation technologies are decanter centrifuge and screw press while also belt screens, bow screens and rotary screens are common. As seen in Figure 4.3, the two first mentioned are the most efficient in reaching high dry matter content in dry fraction. (Al Seadi, et al., 2013b)

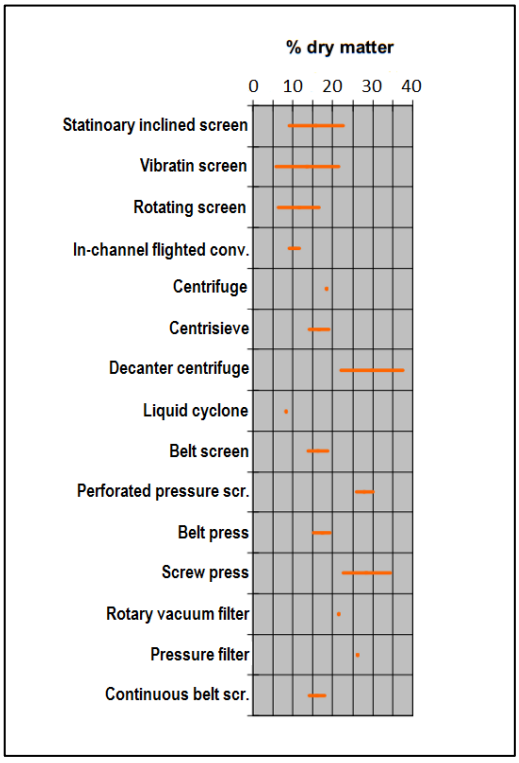

Figure 4.3 Content of dry matter in solid fraction after different solid-liquid separation technologies for livestock manure. Adapted from Ford & Fleming (2002).

Screw press separators are suitable for digestates rich in fibers, e.g. energy crops, and can treat large amount of matter producing solid fraction of 25 – 35 % DM content, depending on the feedstock (Hahn & Hoffstede, 2010). While investment cost and energy consumption are low, generally 0.2 – 2 kWh m^{-3} (Williams & Esteves, 2011) (Hjorth cited by Luostarinen et al. (2011)), the screw press separator cannot separate sludge fractions unlike decanter centrifuge, which is also proper for manure and wastewater sludges. Separation efficiency of decanter centrifuge is higher but it also consumes more energy, often more than 2 kWh m^{-3} (Williams & Esteves, 2011) (Hjorth cited by Luostarinen et al. (2011)). The separation may be enhanced through flocculation of dry matter and phosphorous by suitable polymers (Hjorth, et al., 2010). (Al Seadi, et al., 2013b)

Since this study aims at processing high quality end products from wet AD residue, the separation efficiency should be as high as possible. Thus, the decanter centrifuge is considered as the main application for solid-liquid separation. However, the screw press is also included in the calculations since lower energy consumption is appropriate point of comparison and the technique may be useful when using solid fraction of fibrous digestate in combustion and liquid fraction directly as a fertilizer. (Luostarinen, et al., 2011) A cross profile of decanter centrifuge is shown in Figure 4.4 and energy consumption of a specific device in Figure 4.5.

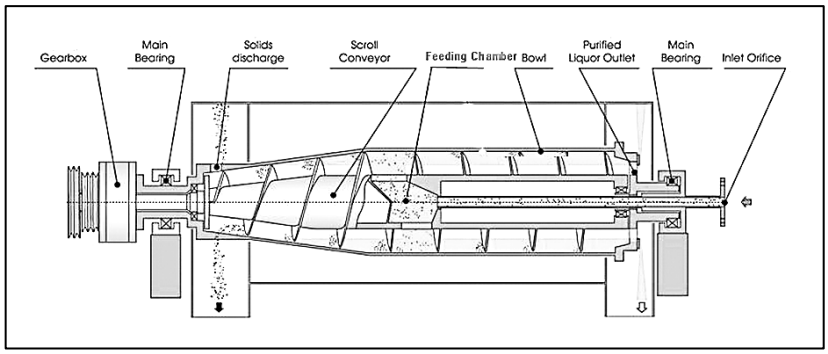

Figure 4.4 Cross section of decanter centrifuge with separate heavy and light liquid separation. Adapted from GN Centrifuge (2013).

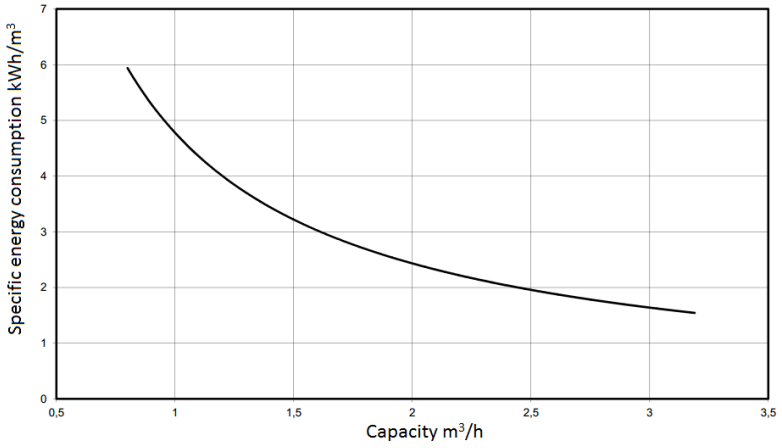

Figure 4.5 Energy consumption of a UCD 205 decanter centrifuge by GEA Westfalia. Adapted from GEA (2014).

4.3 Solid fraction treatment

4.3.1 Drying

When further decrease in water content is intended, the solid fraction of the digestate may be *dried* thermally to dry matter content of over 90 %, as seen in Figure 4.6. The drying process is energy intensive and majorly dependent on availability of waste heat, which, however, is often generated nearby in the biogas combustion (Kratzeisen, et al., 2010). Higher dry matter content enables affordable transportation and treatment of the digestate, for example spreading to a field, or combustion due to increased heating value. Digestate in DM content of 85 – 90 % is stable, nearly odorless, does not mold and may be used in energy production similarly to peat. However, odor and ammonia emissions are generated as the digestate dries. According to fertilizer legislation in Finland, dry matter content of 90 % proves hygiene of the fertilizer product (24/11 Appendices I-IV, 2011). (Hupponen, et al., 2012)

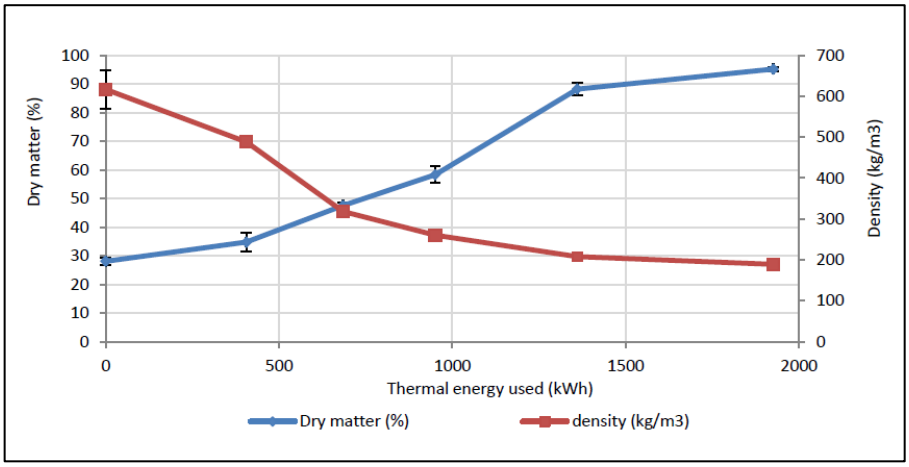

Figure 4.6 The dependence of DM content and density of digestate fibers on thermal energy consumption in the thermal drying trial. Adapted from Shirani & Evans (2012).

The digestate is combustible with 40 – 60 % share of DM but in this case, the matter becomes sticky and the handling is difficult. (Hupponen, et al., 2012) In order to obtain a status of a standardized fuel, the digestate should meet requirements of waste derived fuel or solid recovered fuel (EN 15359:2011) (King, et al., 2013). The classification of solid recovered fuels is seen in Table A2.1 of Appendix 2: since LHV of thermally dried digestate (DM >90 %) is generally between 10 – 17 MJ/kg (Partanen, 2010) (Shirani & Evans, 2012), it may reach class 3 or 4 standardization. Pelletized digestate cannot be standardized as a non-wood fuel pellet, since the requirements of EN 14961-6:2011 are not reached (Zeng & Pollex, 2012). Table 4.3 presents two thermally dried Finnish digestate products.

The heat may be brought to the solid digestate via convection, contact or radiation, two first of which are the commonly used. Generally, convection is applicable when hot flue gases are available and contact if hot steam may be utilized. Convection drying technologies include e.g. drum dryer, belt dryer and flash dryer while contact drying includes e.g. disc dryers and paddle dryers. Fluidized bed dryer is a mixture of

the two. Energy consumptions of different thermal dryer types are shown in Table 4.4. The technologies are mainly based on sludge drying: thermal drying is also an option for sludge stabilization (Pöyry Environment Oy, 2007). (Hupponen, et al., 2012)

Drying generates effluent, odors and air emissions, e.g. ammonia gas, which require treatment. Part of the readily available nitrogen as NH_4^+ is volatilized as NH_3 and the nutrient value of the matter is reduced. However, phosphorous, which serves as the main fertilizer component in the solid fraction, remains. (Frischmann, 2012) Also, in Finland, composting has been used to dry sludges and solid digestates for later energy recovery but, due to renewed waste legislation, combustion of such composts has ceased (Partanen, 2010).

Table 4.3 Two examples of thermally dried digestate products from Finland. (Hupponen, et al., 2012)[1] (AVI, 2013)[2] (MTT, 2012)[3]

Product	*Technology*[1]	*Organics and DM*	*Other properties*
Secondary fuel by Vapo Oy [2]	*Belt dryer (convection drying)*	*DM 90 – 93 %*	*N.S.*
Soil improver pellet by Lakeuden Etappi Oy [3]	*Disc dryer (contact drying)*	*Organics 48 %* *DM 88 %*	*N 3.2 kg/m*^{3} *P 0.1 kg/m*^{3}

Table 4.4 Specific energy consumptions of thermal dryers. Adapted from Bennamoun et al. (2013).

Dryer type	*Specific energy consumption (kWh t*$^{-1}$ *water evaporated)*
Belt dryer	700 – 1140
Drum dryer	900 – 1100
Flash dryer	1200 – 1400
Disc dryer	855 – 955
Paddle dryer	800 – 855

4.3.1.1 Solar drying

Also solar energy may be used as a radiative heating source in a preferably covered space, e.g. a greenhouse, to avoid ammonia emissions. In this case, the digestate does not always require previous separation and the process may be enhanced by hot gases or floor heating, if waste heat is available. (Frischmann, 2012) Similarly to convection and contact drying, the technology has been developed for sludge drying. The energy demand of thermal drying may be decreased by solar energy while, however, considerable surface area and extra heating are often required. (Hupponen, et al., 2012) Also, according to Vetter & Burger cited by Rehl & Müller (2011) the aeration and mixing the digestate to DM content of 65 % required 200 kWh per tonne

water removed. Due to lack of data in reaching higher DM contents and seasonal conditions of Finland, solar heating is not covered by calculations of this study.

4.3.2 Composting

In *composting*, the matter is degraded in aerobic conditions while heat and CO_2 are produced (i.e. in the presence of oxygen). Composting is applied to the solid digestate to speed up degradation of remaining organics to humus and ammonia to nitrate, and thus, ensure stability of the matter and increase its quality. High-quality compost provides humic substances, nitrates and micro-organisms, improving also water retention and pH buffer capacity of the soil. Due to high water content, the digestate is often mixed with additional organic matter in compost. Such matter may be e.g. green waste (Frischmann, 2012), peat, wood chips, other wood residues or mixture of those (Latvala, 2009). Mature compost is suitable for use as a fertilization product: organic fertilizer, soil improver or growing medium. (Saveyn & Eder, 2014) According to the designation list of fertilization products (Evira, 2013b), organics content of the compost products deriving entirely or partly from digestate should be minimum 25 % of dry matter.

When digestate is composted, it should be loosened due to lack of oxygen. Compost may reach temperature level of over 70 °C due to intense microbial activity, which, if maintained for sufficient time frame, results in pasteurization of the digestate (Saveyn & Eder, 2014). However, also additional heat is often supplied to improve the composting process, resulting in energy consumption. In optimal conditions, desired maturity is achieved in one to two weeks. As a downside, a substantial part of the nitrogen may be lost as ammonia emission during composting (Luostarinen, 2013), the process requires space and may generate odorous gases. (Latvala, 2009) The common composting techniques in Finland are windrow composting and tunnel composting (Lohiniva, et al., 2001). Due to low energy consumption, windrow is chosen to serve for this study. Aerobic degradation occurs also in storing of digestate, and is, to set apart from proper composting, called aging (Partanen, 2010).

4.3.3 Granulation and pelletizing

Solid digestate may be *pelletized* or *granulated* into desired physical size and density before, during or after thermal drying. As a result, the matter does not dust and becomes more dense and easier to handle. Grains and pellets of digestate origin may be used in combustion or fertilization yet the binding might reduce solubility of the nutrients (Latvala, 2009). Low density grains are produced e.g. in a mixer, fluidized bed dryer or drum dryer whereas better quality is reached by pressurized compression (Genskow cited by Hupponen et al. (2012)). Pressurized technologies include extruders, tablet presses, molding presses (Figure 4.7) and roll presses. Binding agent may be used to strengthen the structure of the grains or pellets. (Hupponen, et al., 2012) Due to better product quality, only pressurized pelletizing is considered in this study.

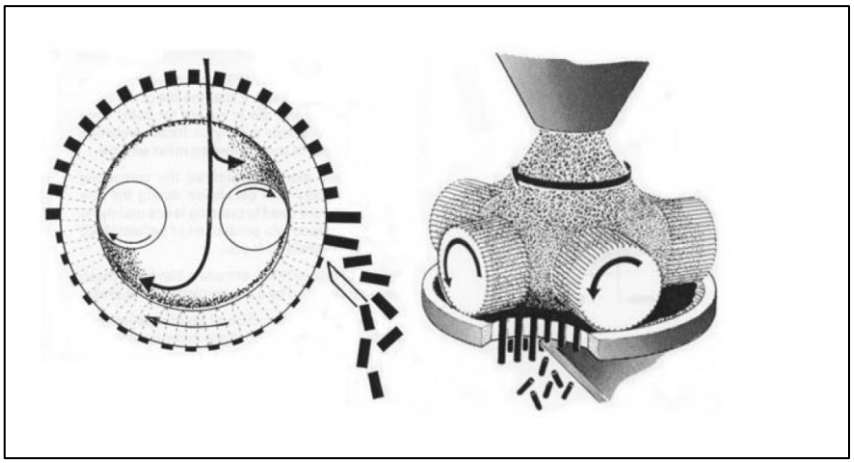

Figure 4.7 Operational principles of two molding presses. Payne cited by Hokkanen (2009).

4.4 Liquid fraction treatment

4.4.1 Nutrient recovery

The nutrient recovery may be applied to liquid digestate for two reasons: to reduce nitrogen content since it is often the limiting factor in land application and causes eutrophication, or to obtain the nutrients in a concentrated form (Al Seadi, et al., 2013b). The article by Lebuf et al. (2012) presents different methods for the nutrient recovery, e.g. ash nutrient extraction (solid fraction), Anammox process, membrane filtration, ammonia stripping and evaporation, three last of which are the most common in Central Europe (Fuchs & Drosg, 2013). In nutrient extraction from ash, chemical agent and heat are utilized to recover phosphorous from the ash containing also K and some heavy metals after digestate combustion. Respectively, when the digestate is pyrolyzed, the nutrients end up in the char, in higher amounts than in combustion. (Lebuf, et al., 2012)

4.4.1.1 Membrane filtration

The membrane filtration is currently the most feasible complete conditioning method, splitting the liquid digestate into fractions of concentrated nutrients and nearly drinkable water (Fuchs & Drosg, 2013). However, purified water covers only around half of the digestate since the nutrients are recovered in several streams of different properties, which require treatment (Fuchs & Drosg, 2013). Due to high energy demand and several special layers, the membrane technology is expensive. In membrane filtration, liquid containing only small particles is forced through a membrane with pressure. Membrane filters impurities from the water normally in three phases: microfiltration, ultrafiltration and reversed osmosis. Micro- and ultrafiltration remove suspended solids and macromolecules in order to prevent blocking of reverse osmosis layer. (Lebuf, et al., 2012) To achieve desired ammonia recovery, normally three reverse osmosis steps are needed. (Al Seadi, et al., 2013b)

4.4.1.2 Evaporation

When waste heat is available, also the liquid fraction or sometimes even the whole digestate may be dried by *evaporation*. In literature this is also known as *concentration*, since, apart from thermal drying of the solid digestate, the aim is to gain nitrogen rich liquid by preserving also the volatile nutrients. Thus, sulfuric acid is added to lower the pH to prevent evaporation of ammonia, which increases cost of the process. (Al Seadi, et al., 2013b) Evaporation may be considered as complete conditioning process when the condensate water is purified before discharge (Al Seadi, et al., 2008). Similarly to thermal drying, lowered transportation costs are gained since volume of the matter is typically reduced by 50 % (Fuchs & Drosg, 2013).

4.4.1.3 Ammonia stripping

Contrary to ammonia gas emissions in drying, the volatilization of ammonia is intentional in *ammonia stripping*. Previously ammonia stripping has been used successfully for removal of nitrogen from different wastewaters. Air or steam is blown through the liquid digestate in a packed tower converting ammonium to ammonia gas. The ammonia volatilization is majorly dependent on the pH value of digestate, optimum of which is around 10.5, while also heating enhances stripping efficiency, as seen in Figure 4.8. (Guštin & Marinšek-Logar, 2011) After stripping, the ammonium can be recovered from the strip gas into a fertilizer product, e.g. ammonium sulphate by scrubbing (Frischmann, 2012). Due to main advantages of ammonia stripping, relatively simple and common technology and quality ammonium products (Al Seadi, et al., 2013b), it serves as the nutrient recovery technique in the calculations.

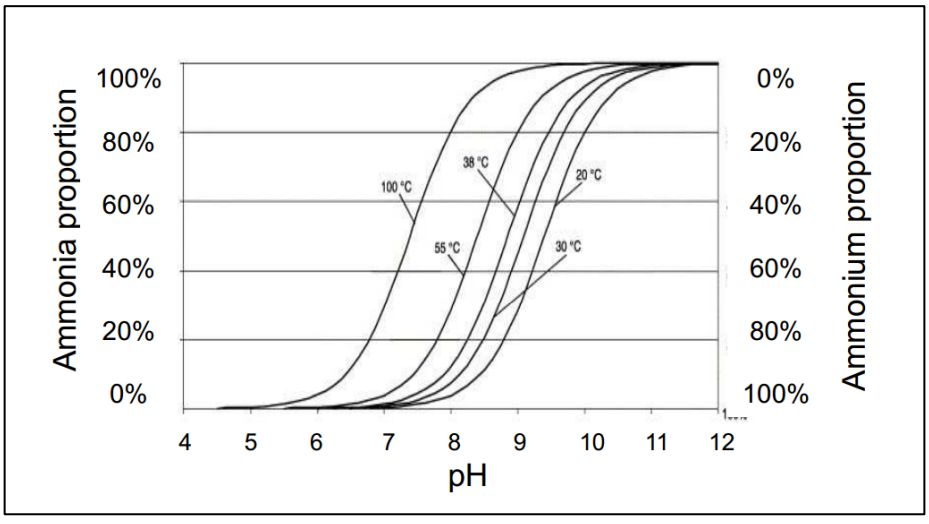

Figure 4.8 Dependency of ammonia and ammonium share on pH and temperature. Fricke cited by Williams & Esteves (2011).

5 ENERGY AND GHG EMISSIONS IN PROCESSES AND APPLICATIONS

Chapter 5 introduces the base data of energy efficiencies and greenhouse gas emissions in selected digestate applications and required processes. The data will be used in the following Chapter as energy balances and GHG emissions of processes and applications are linked together and calculated. Also, the effects of the processes on main digestate properties are estimated. Scientific articles on the field focus mainly on separate processes whereas Rehl and Müller (2011) have performed life cycle assessment on seven different digestate treatment chains. In the Finnish literature, Myllymaa et al. (2008b) have studied CO_2 equivalent GHG emissions from land applications of digestates deriving from biowaste and sewage sludge.

This study covers energy efficiencies and indirect GHG emissions of four different end product chains, illustrated in Figure 5.1. Also the changes in digestate properties throughout the chains are taken into account. The digestate processing requires energy while applications substitute use of fossil products and, therefore, save emissions and energy from the production of those. The studied end products are soil improver-growing medium, solid fuel (fertilizer pellet), ammonium sulphate fertilizer and liquid fertilizer. It should be noted that in Finland the liquid stream from mechanical separation is often, for example in the list of designations by Evira, called reject water while in this study the nomination is liquid fertilizer.

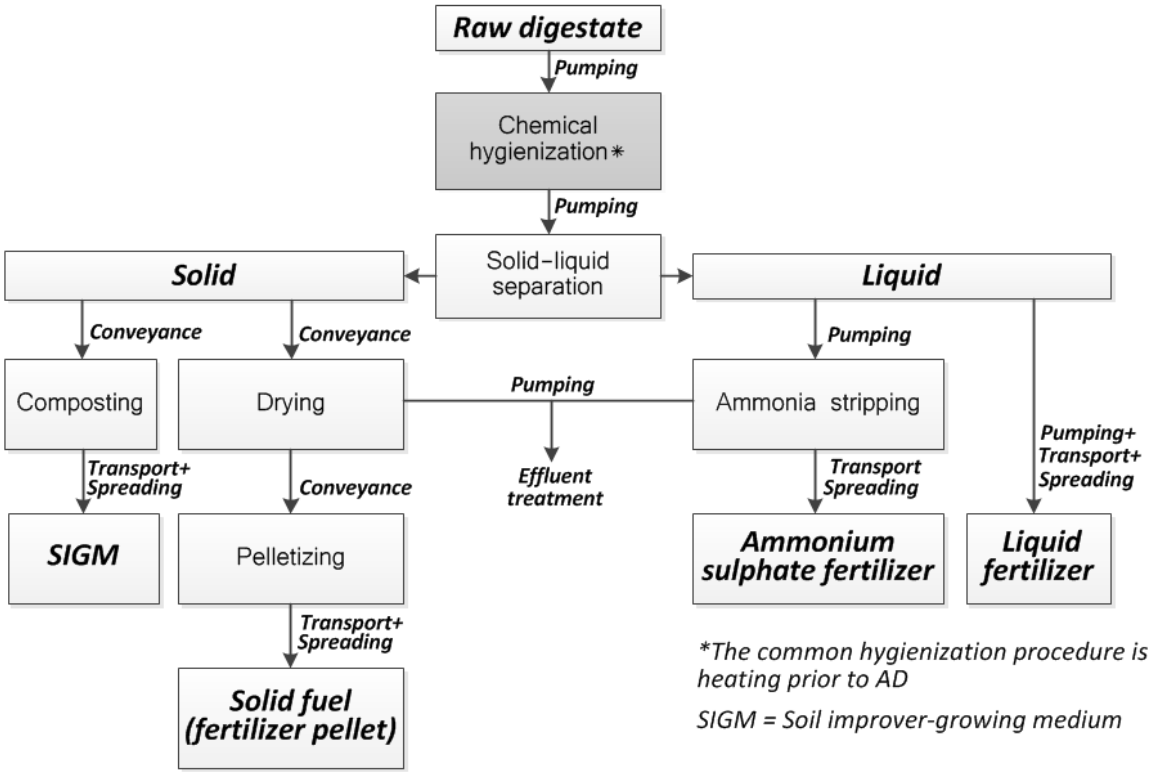

Figure 5.1 The processes, auxiliaries and applications studied in the energy balance and GHG emission calculations of this Thesis.

5.1 Data processing

The final energy consumptions of different digestate application chains are estimated as *primary energy demand (PED)*. Primary energy stands for energy extracted or captured from nature in its first recoverable state (Keto, 2010). In this study, the primary energy sources include both renewable and non-renewable energy sources while Rehl and Müller (2011) considered only non-renewable energy in their LCA study on digestate processing. Often, the energy efficiencies of separate processes are provided as kilowatt hours of secondary energy, generally per tonne matter treated. For the final calculations, the secondary energy use is converted to PED per tonne raw digestate using *primary energy factor (PEF)*.

Finally, the energy uses of applications and required processes are linked together. The properties of digestate are included in calculations, since the processes are dependent on e.g. mass of the matter and applications on e.g. nutrient content. The observed properties, which are discussed further in the Section 5.7, are mass, water, DM, organics and content of nutrients. In order to improve energy, emission and property data processing and comparison, an excel-tool is built. Further information on the tool functions are provided in Chapter 6.

Since carbon dioxide is considered the most important greenhouse gas (IPPC, 2007), the GHG emissions are often, and also in this study, estimated as CO_2 equivalents by global warming potential within 100 years i.e. GWP 100. As the digestate is renewable bio-origin material, all direct GHG emissions originating from the matter, e.g. from combustion, are considered CO_2-neutral and ignored in the GHG calculations. Also volatilization of nitrogen in field applications is neglected since the land application is considered as the reference procedure in digestate treatment. Energy demands on main and auxiliary processes are converted to CO_2 equivalents using *specific emissions factors (SEFs)*. CO_2 equivalents include direct emissions of CO_2, CH_4, N_2O and SO_2, and indirect NO_x, CO and NMVOC emissions as defined in *the Finnish National Inventory Report under the UNFCCC and the Kyoto Protocol* (Statistics Finland, 2009).

5.2 Energy consumptions in processes

To obtain extensive results, the data of energy demands of the main processes, solid-liquid separation, composting, drying, pelletizing and ammonia stripping, are collected separately from both scientific researches and commercial sources. The division is not applied on chemical hygienization and auxiliaries due to scarcity of data and to simplify the calculations. The values from scientific researches are considered as the objectives, and thus, the optimum of a provided range is generally chosen to be used in the calculations. As for commercial data, the average or median value of a range is used to represent current standard situation.

5.2.1 Chemical hygienization

Heating is usually defined as the general hygienization process while alternative techniques may as well be validated or approved nationally. Also, these techniques could be applied to digestate of sewage sludge origin, which is not covered by ABPR but often requires stabilization and sanitation after AD. In calculation of this study, the alternative sanitation is achieved by chemical treatment of whole digestate, since drying, combustion and composting are applied only to solid fraction.

However, due to several uncertainties, e.g. in sanitation efficiency of chemical treatment and biogas production improvement of thermal pretreatment, the hygienization is considered as an optional treatment in the calculations. The common chemical treatment processes are *acid-peroxide conditioning* and *alkaline stabilization* (Pöyry Environment Oy, 2007). The KemiCond process, representing the first mentioned, requires little energy for the chemical production (Svoboda, 2003), and thus, serves as the alternative hygienization method in the calculations, featuring values presented in Table 5.1.

Table 5.1 Primary energy balances in thermal hygienization and chemical treatment.

Feature	***Unit***	***Standard heating***	***Chemical (KemiCond)***
Chemical consumption	*g/kg* $DM_{digestate}$	-	*Sulphuric acid* 234[I] *Hydrogen peroxide* 27[I]
Primary energy demand	*kWh/*$t_{digestate}$	69.6[II]	9.1[III] *Chemicals production*
Biogas production improvement as PED	*kWh/*$t_{digestate}$	0 – 69.3[IV]	-
Used in calculations			
Primary energy savings in chemical hygienization	*kWh/*$t_{digestate}$	60.5 (-8.8[V])	

I (Thunberg, 2010)

II *Energy consumption of standard heating: 48.8 kWh/t feed.* (Luste & Luostarinen, 2010)*, Digestate: DM 5.7 %* (Fachverband Biogas, et al., 2013)*, 56 % decrease in DM content in AD* (Crolla, et al., 2013)*. Converted to PED using primary energy factor 1.33 (Table 5.10)*

III *Digestate: DM 5.7 %, energy consumption of chemical production: 77 kWh electricity per tonne sulphuric acid* (AVI, 2011) *and 2600 kWh (incl. electricity, heat, natural gas and process gas) per tonne hydrogen peroxide* (Kaakkois-Suomen Ympäristökeskus, 2005). *Converted to PED using average of primary energy factors of heat and electricity: 1.8. (Table 5.10.)*

IV *Maximum biogas production improvement due to hygienization 64.6 kWh PED/t feed.* (Luste & Luostarinen, 2010) (Paavola & Rintala, 2006).

V *Full biogas production improvement: 60.5 – 69.3 kWh/t digestate*

The possible biogas production improvement, observed by Paavola & Rintala (2006), is also noted in a special case of the calculations, generating lower energy consumption for chemical hygienization. Difference between the process electricity consumptions and auxiliaries of chemical use are considered negligible. Due to lack of energy consumption data available, division into scientific and commercial values is ignored when evaluating energy balances of hygienization.

5.2.2 Solid-liquid separation

The machinery in solid-liquid separation consumes energy, demand of which is determined by the used technology and volume capacity. Due to high efficiency in dry matter and nutrient separation, decanter centrifuge is also suitable for sludge-like digestates and is considered, in this study, as the primary technology for solid-liquid separation. Screw press is observed as a special case since the low energy consumption and lower separation efficiency of nitrogen may generate energy benefit when the solid fraction is used in land application, i.e. as soil improver-growing media.

An energy demand of a specific device is highly dependent on the volume of the digestate, and therefore, accurate dimensioning, as seen in Figure 4.5. According to Al Seadi et al. (2013b), the performance values of devices from different brands are similar to each other. Scientific sources presented in Table 5.2 suggest optimum energy consumption of decanter centrifuge to be around 1.8 kWh per tonne, which is used as optimum in the energy efficiency study of this Thesis. For screw press, the optimal energy consumption is evaluated to be 0.4 kWh t^{-1}, since the lower values have only been presented in one source of collected data by Williams & Esteves (2011). The average commercial values are, as seen in the table, around twice as high.

Table 5.2 Electricity demands of decanter centrifuges and screw presses in scientific and commercial literature sources.

	Source	***Electricity demand of decanter centrifuge*** *kWh/t*	***Electricity demand of screw press*** *kWh/t*
Scientific research or unspecified	*Williams & Esteves* (2011)	1.8 – 7	0.24 – 1.1
	Al Seadi et al. (2013b)[I]	1.8	0.4 – 0.5
	Hjorth cited by Luostarinen et al. (2011)[I]	2.1 – 5.6	0.5 – 2.1
Used in calculations as optimum value		1.8	0.4
Commercial	*Møller et al.* (2002)[I]	2.6 – 5.9	0.6 – 1.3
	Wesnæs et al. (2013)[I]	2.0 – 4.2	-
Used in calculations as standard value		3.5	0.9

I *Density of raw digestate: 950 kg m^{-3}* (Bauer, et al., 2009)

5.2.3 Composting

Composting process requires often energy since it is enhanced by aerating and heating. In this study, windrow composting, equipped only with aerating machinery, serves as the main composting method due to low energy consumption. Value provided by Lehto, cited by Myllymaa et al. (2006), is assessed to represent optimum while the commercial value is provided by two studies, as shown in the Table 5.3.

Table 5.3 Electricity consumption in windrow composting.

Source		***Electricity demand of windrow*** *kWh/t*
Scientific research or unspecified	*Lehto cited by* (Myllymaa, et al., 2006)	10
Used in calculations as optimum value		10
Commercial	*Bergmann & Lenz cited by White et al.* (1995)	18
	Boldrin et al. (2009)	0.02 - 20
Used in calculations as standard value		18

5.2.4 Thermal drying

In this study, the solid digestate is, when not composted, dried to DM content of 90 % to obtain class 4 or 3 status of solid recovered fuel (CEN/TS 15359, Appendix 2). Mercury and chlorine contents of digestates were below class 4 limits in the study by Shirani & Evans (2012) while such values cannot be verified in this study. Drying is an energy intensive process since water is removed from the digestate by vaporization. Specific heat capacity of water is around 4.19 kJ kg^{-1} K^{-1} and specific heat of evaporation is 2260 kJ kg^{-1} (Seppänen, et al., 2005). Thus, vaporizing one tonne of 20 °C water consumes 720 kWh energy (losses not included) while, for example, energy use of mechanical separation is around 0.2 – 6.7 kWh per tonne digestate. Thermal drying is considered to affect only water content of the matter.

In the report by Lohiniva et al. (2001) the energy consumption of thermal dryer was estimated to vary from 830 to 970 kWh per tonne water evaporated. Additionally, electricity consumption of dryer was estimated to range from 5.1 to 6.4 kWh per tonne mechanically dewatered digestate (density 780 kg m^{-3}, Bauer et al. (2009)) or per 600 kg water evaporated in drying from 30 % DM to 90 % DM. This is similar to other sources presented in Table 5.4, and thus, the optimal thermal dryer is assumed to consume 830 kWh thermal energy and 8.5 kWh electricity per tonne water evaporated in calculations of this study. According to Arlabosse et al. (2012) for sludge dryers the relation of heat supplied over enthalpy of water vaporized ranges from 1.15 to 1.65, with median of 1.35. This indicates energy consumption of 830 – 1190 kWh and median value 970 kWh per tonne 20 °C water evaporated at sludge dryer. The median value serves as the energy consumption of commercial device in the calculations, as shown in Table 5.4. The dependence of water removal and thermal energy input is assumed to be linear till DM content of 95 % to simplify the calculation. In truth, the linearity is not perfect as seen in Figure 4.6.

Table 5.4 Energy consumptions of thermal dryers according to scientific researches and commercial sources.

Source		***Thermal energy demand (+ electricity)*** *kWh / tonne water vaporized*
Scientific research or unspecified	*Theoretical*	720
	Lohiniva et al. (2001)	830 – 970 (+ 8.5 – 10.7)
	Bennamoun et al. (2013)	700 - 1400
Used in calculations as optimum value		830 (+ 8.5)
Commercial	*Arlabosse et al.* (2012) *applied to theoretical*	830 – 1190, *median* 970
Used in calculations as standard value		970 (+ 9.6)

5.2.5 Pelletizing

Pelletizing consumes energy as the matter is pushed into a desired form with pressure. Energy calculations include also milling, in which the particle size is

reduced, as a part of pelletizing process. The material flow is assumed to be unchanged. According to report by Shirani & Evans (2012), the milling consumed 113 kWh per tonne thermally dried digestate and pelletizing, including ancillary machinery, 128 kWh per tonne milled digestate. In comparison, the study by Lootsma et al., cited by Kratzeisen et al. (2010), indicates energy demand of 150 kWh per tonne digestate pelletized, although, lacking details of machinery. The first mentioned values derive from commercial practice and represent the current standard situation in the calculations. The latter serves as the optimum value, as presented in Table 5.5.

Table 5.5 Total electricity consumption of milling and pelletizing equipment according to the scientific research by Lootsma et al., cited by Kratzeisen et al. (2010), and the commercial study by Shirani & Evans (2012).

Source		***Electricity demand of milling*** *kwh/t*	***Electricity demand of pelletizing*** *kwh/t*
Scientific research or unspecified	*Lootsma et al., cited by Kratzeisen et al. (2010)*	incl.	150
Used in calculations as optimum value		150	
Commercial	*Shirani & Evans* (2012)	113	128
Used in calculations as standard value		240	

5.2.6 Ammonia stripping

Ammonia stripping is considered as the most feasible nutrient recovery method due to relatively simple and common technology, inexpensive chemicals and recovery of standardized fertilizer products, in this case *ammonium sulphate* $(NH_4)_2SO_4$ (Eekert, et al., 2012). Due to temperature adjustment, chemical use and electricity of pumps and fans, the ammonia stripping is an energy intensive process. In this assessment, product of ammonia stripping is ammonium sulphate solution. Values of energy consumption in ammonium stripping in scientific and commercial sources are presented in Table 5.6.

Table 5.6 Energy consumption in ammonia stripping according to a scientific research and a commercial value.

Source		***Total energy demand***
Scientific research or unspecified	*Maurer cited by Eekert et al.* (2012)	31 *kWh PED/kg N*
Used in calculations as optimum value		31
Commercial	*Lantec cited by Luostarinen et al.* (2011)	125 *kWh/t liquid digestate*[I]
Used in calculations as standard value		125

I *Energy carrier not specified, assumed as thermal energy*

5.3 Energy balance in auxiliary machinery

Auxiliary equipment included in this study are pumps, conveyors, transports, spreaders and effluent treatment facility, use of which are denoted in the flow chart of Figure 5.1. Pumping, conveyance and effluent treatment are driven by electric power while transportation and spreading are powered by diesel. In Finland, majority of the biogas plants are WWTPs or co-digestion plants: therefore the effluent is considered to be pumped to a treatment in a WWTP. The distance of effluent pumping is assumed to be longer than of raw and liquid digestate, and thus, the electricity consumption of pumping is twofold. The values used in the calculations and the sources of those are shown in Table 5.7. The distance of transportation by a semi-trailer truck is assumed to be 20 km while the volume of digestate is ignored since the densities of digestate products are assumed to be roughly equal.

It should be noted that in the list of fertilizer product designations of Evira, liquid stream from mechanical separation is called reject water, while the effluent of this study is produced by thermal drying or ammonia stripping. The effluent quality from such processes is assumed to be appropriate for wastewater treatment process, since generally nitrogen load of mechanically separated liquid fraction causes the most severe problems (Lehto, 2010). To simplify the calculations, the division into scientific optimum and values of current situation values ignored for auxiliary machinery. The energy use of synthetic fertilizer spreading is included in the energy saving of fertilizer replacement.

Table 5.7 The energy demands of required auxiliary processes.

Process	***Source***	***Energy carrier***	***Unit***	***Value***
Pumping (raw and liquid digestate)	*Sandars et al.* (2003)	*Electricity*	*kWh/t*	0.35
Pumping to effluent treatment	*2x Sandars et al.* (2003)	*Electricity*	*kWh/t*	0.7
Conveyance (solid digestate)	*ASCE* (2000)	*Electricity*	*kWh/t*	0.28
Transportation (trailer truck)	*Mäkelä* (2012)	*Diesel*	*kWh/t*	3.4[I,II]
Spreading	*Recchia et al.* (2011)	*Diesel*	*kWh/ha*	75.3[II,III]
Effluent treatment	*Kukko* (2009)	*Electricity*	*kWh/t*	1[IV]

I *Semi-trailer combination with full 25 tonne load, transport distance 20 km*
II *LHV of diesel: 11.5 kWh/kg* (Alakangas, 2000)
III *Cow dung deep fertilizing: 6.55 kg diesel per hectare, considered similar for spreading of both solid and liquid digestates*
IV *Energy consumption of wastewater treatment in a modern plant*

5.3.1 Determining area and energy demand of spreading

The number of hectares fertilized is dependent on the amount of nutrients applied. According to Partanen (2010), in Finland the amount of fertilizers allowed is generally determined, when total nitrogen is the limiting factor, by the European Nitrate Directive (91/676/EEC) or, when total phosphorous, by the terms of the environmental aid (Mavi, 2009). Since these restrictions aim to match the nutrient uptake of the plants with the nutrient content in digestate, those are used in

calculations to determine area of land application for digestate. The impurities in Finnish digestates are generally below the limits (Partanen, 2010) (Marttinen, et al., 2013). The directive defines total nitrogen usage maximum of 170 kg per hectare while the limit for total phosphorous is dependent on soil fertility class and cultivated plant. For cultivation of grain at fertility classes good and sufficient, which cover majority of fields in Finland, the limit varies between 4 and 14 kg per hectare. For the calculations, value of 8 kg per hectare is used, which is limit for cultivation of rye and wheat at class good and of oat at class sufficient. The environmental aid was valid until end of 2013 but similar act is expected to be extended.

According to the aid, for digestate deriving entirely or partly from sewage, 40 % of total phosphorous is taken into account and for other digestates soluble phosphorous in 1:5 aqueous extraction. The latter, however, is observed to significantly underestimate the amount of soluble phosphorous, which for Marttinen et al. (2013) recommend using factor of manure fertilizer: 85 % of total phosphorous. Therefore, in calculations for both spreading, as marked in Table 5.8, and substitution of synthetic fertilizers, factors 0.4 and 0.85 are used to reduce applicability of phosphorous in digestates deriving entirely or partly from sewage sludge and other digestates, respectively. (Mavi, 2009) Due to more than 10-fold applicability of nitrogen by mass, the phosphorous is often the limiting factor. In this study, only in the application of ammonium sulphate fertilizer, the nitrogen would define the area of spreading: this is, however, also ignored due to negligible energy use.

Table 5.8 Application area and demand of diesel energy per kg of N_{tot} or P_{tot} in digestate spread.

Fertilizer compound	*Source*	*Factor*	*Unit*	*Value*
N	*The Nitrate Directive* (91/676/EEC)	*Application limit*	*ha/kg N*	0.0067
P	*The Environmental aid* (Mavi, 2009)	*Application limit*	*ha/kg P*	0.125
N in digestate	*Table 5.7*	*Energy demand*	*kWh/kg N*	0.5
P in digestate	*Table 5.7*	*Energy demand*	*kWh/kg P*	3.8 [I] 8.0 [II]

I *Derives entirely or partly from sewage sludge: 0.125*0.4 ha/kg*

II *Does not contain sewage sludge origin matter: 0.125*0.85 ha/kg*

5.4 Energy balances in applications

5.4.1 Land applications

The land applications are considered to generate indirect energy savings due to substitution of synthetic fertilizer usage and SIGM application also by replacing peat production. The energy demands used in the calculations for production and spreading of synthetic fertilizers and peat are seen in Table 5.9. Since 40 % of the phosphorous in digestate deriving partly or entirely from sewage sludge and 85 % in other digestates are considered in fertilization as discussed in Section 5.3.1, the respective factors 0.4 and 0.85 are also used in calculations as substituting the synthetic fertilizers.

Table 5.9 Primary energy demands of synthetic fertilizer and peat use. Only spreading of synthetic fertilizers is considered as auxiliary in the calculations due to negligible energy use of e.g. transportation (Table 5.8).

Operation	***Source***	***N-fertilizer*** *kWh/kg N*	***P-fertilizer***[I] *kWh/kg P*	***Peat*** *kWh/kg peat*
Production	*N: Kongshaug cited by Lako* (2009) *P: Berglund & Börjesson* (2006)	9.1 – 13.4	2.2	0.058[II]
Spreading	*Recchia et al.* (2011)*, Table 5.9*	0.12[III]	2.2[III]	-
	Used in calculations	10.8[IV]	2.2 + 2.2	0.058

I *Due to the environmental aid, 40 % of the phosphorous in digestate deriving entirely or partly from sewage sludge and 85 % in other digestates is taken into account in substitution of synthetic P-fertilizer in the calculations*

II *LHV of peat 13.955 MJ/kg, 1.5 % of energy content consumed in harvesting* (Aiken, et al., 1983)*, due to low carbon content, one tonne digestate is considered to replace 0.2 tonne peat in the calculations*

III *Top dressing: 1.53 kg diesel per ha* (Recchia, et al., 2011)*, LHV of diesel: 11.5 kWh/kg* (Alakangas, 2000)*, considered as PED, only spreading of P-fertilizer is considered due to negligible value of N-fertilizer spreading*

IV *Average of the range*

Ammonia production is the most common fertilizer manufacturing process and also the most energy intense. The phosphorous production consumes less energy but since phosphorous is often the limiting factor in land application of digestate, the energy intensity of ammonia is leveled. According to Johnson et al. (2013), the energy consumption of manufacturing of P-fertilizer could be covered by steam export from production of required intermediate, sulfuric acid. This is, however, ignored due to lack of information on applying the procedure in the fertilizer industry.

5.4.2 Combustion

The combustion of thermally dried digestate generates energy surplus, which may be utilized as heat or electricity. Amount of energy produced is dependent on the heating value of the matter and the combustion efficiency. The aim of solid fuel production in this study is to provide class 3 or 4 fuel of standard CEN/TS 15359. The lower heating value of digestate is determined by equation (Alakangas, 2009),

$$q_{l,ar} = \left[\left(\frac{q_{l,daf} * (100 - A_d)}{100}\right) * \left(\frac{100 - M_{ar}}{100}\right)\right] - 0.02443 * M_{ar} \qquad (3)$$

where

$q_{l,ar}$ *lower heating value as received, MJ kg^{-1}*
$q_{l,daf}$ *lower heating value dry basis and ash-free, MJ kg^{-1}*
A_d *ash content in dry matter, %*
M_{ar} *water content, %*

According to calculations by Huhtamäki, cited by Partanen (2010), the lower heating value of digestate on dry basis and ash free is 22 MJ kg^{-1}, which is used as a standard value in the calculations. The water content is decreased to around 10 % in thermal drying and the ash content is dependent on properties of raw digestate. The LHV based energy content of digestate stands for the primary energy in its combustion:

$$E_{p,c} = \frac{q_{l,ar}}{3.6} \quad (4)$$

where

$E_{p,c}$ *primary energy content, kWh kg^{-1}*

5.5 Primary energy conversion factors

To enable concatenating of processes in terms of energy balance and GHG emissions, the units of energy consumption should be similar. Thus, the energy consumption of application chains is determined as kWh of primary energy demand (PED) per tonne digestate treated. In this study, the primary energy sources include both renewable and non-renewable energy sources while Rehl and Müller (2011) considered only non-renewable energy. The energy use of processes is usually given as kWh secondary energy demand per tonne matter processed but in some cases directly as PED. These are converted to primary energy using *primary energy factor (PEF)*, which represents energy input from primary energy source over energy content of energy carrier. Table 5.10 presents primary energy factors for energy carriers used in the processes; electricity, heat and diesel.

Table 5.10 Primary energy factors (PEFs) of electricity, heat and diesel in Finland.

Energy carrier	***Processes and auxiliaries***	***Source***	***Energy source***	***PEF*** *kWh/kWh*
Electricity	*Solid-liquid separation Composting, Pelletizing Pumping, Conveyance Effluent treatment*	Keto (2010)	*Finnish average*	1.97[I]
Heat	*Hygienization, Drying Ammonia stripping*[II]	Keto (2010)	*Biogas*	1.33[III]
Diesel	*Transportation, Spreading*	Bröckl et al. (2010)	*Diesel*	1.35[IV]

I *CHP generation allocated by energy method*
II *Scientific value provided as primary energy*
III *Industrial steam (1.27) produced from biogas (1.05)* (Bröckl, et al., 2010)
IV *Assumed equal to fuel oil*

5.6 Greenhouse gas emissions

In this study, the greenhouse gas emissions derive from energy uses of processes while the applications generate emission savings through energy content of solid fuel or as production of peat and synthetic fertilizers is avoided. Since the digestate is bio-origin matter, which is applied to land by standard, the direct emissions from digestate are considered CO_2-neutral. Use of the digestate as fertilizer pellet, ammonium sulphate fertilizer or liquid fertilizer substitutes synthetic fertilizers while application as soil improver-growing media also restricts harvesting of peat for compost. According to report by Myllymaa et al. (2008a), digestate could replace peat by ratio 1:1 in SIGM, which is, however, in this study considered oversized due to low carbon content of digestate. In the calculations, one tonne digestate is estimated to replace 0.2 tonne peat. The emission values for synthetic fertilizer and peat usage are presented in Table 5.11.

Table 5.11 CO_2 equivalent emissions (by GWP 100) of synthetic fertilizer and peat use. Only spreading of synthetic fertilizers is considered as auxiliary in the calculations due to negligible energy use of e.g. transportation (Table 5.8).

Operation	***Source***	***N-fertilizer*** $kg_{CO2\text{-}EQ}/kg\ N$	***P-fertilizer***[I] $kg_{CO2\text{-}EQ}/kg\ P$	***Peat*** $kg_{CO2\text{-}EQ}/kg_{digestate}$
Production	*Boldrin et al*. (2009)	4.8 – 13.0	0.50 – 3.1	0.11 – 1.2[II]
Spreading	*Table 5.9, Table 5.12*	0.03[III]	0.53[III]	-
Used in calculations		8.9[IV]	1.8[IV] + 0.53	0.11

I *Due to the environmental aid, 40 % of the phosphorous in digestate deriving entirely or partly from sewage sludge and 85 % in other digestates is taken into account in substitution of synthetic P-fertilizer in the calculations*

II *Range of replacing 0.2 to 1 tonne peat, due to low organic content, one tonne digestate is considered to replace 0.2 tonne peat*

III *Emissions from diesel consumption of spreading, only spreading of P-fertilizer is considered due to negligible value of N-fertilizer spreading*

IV *Average of the range*

5.6.1 GHG conversion factors

Greenhouse gas emissions or savings of main processes, auxiliaries and solid fuel application derive from the generated energy balances. The energy demands of processes are converted to CO_2 equivalents using specific emission factors (SEFs) of different energy carriers provided by Keto (2010). SEFs include direct emissions of CO_2, CH_4, N_2O and SO_2, and indirect NO_x, CO and NMVOC emissions by GWP 100 (Statistics Finland, 2009). The SEFs are presented in Table 5.12.

Table 5.12 Specific emission factors (by GWP 100) of electricity, heat, diesel and primary energy in Finland.

Energy carrier	***Source***	***Energy source***	***SEF*** $kg_{CO2\text{-}EQ}$ / kWh
Electricity	Motiva (2010)	*Biogas or other renewable*	0
	Keto (2010)	*Finnish average*	0.23[I]
Heat	Motiva (2010)	*Biogas or other renewable*	0
	Keto (2010)	*Finnish average (as industrial steam)*	0.12
Diesel	Statistics Finland (2014)	*Diesel*	0.24
Primary energy	Motiva (2010)	*Biogas or other renewable*	0[II]
	Keto (2010)	*Finnish average*	0.11[III]

I *CHP production allocated by energy method*

II *Applied for scientific value of ammonia stripping and chemical hygienization*

III *Average SEF of electricity and industrial steam (0.175) divided by average PEF of industrial electricity and steam (1.62)*

The energy content of solid fuel is considered, in both cases, to prevent the emissions of Finnish average energy production. Since e.g. energy demand of hygienization is

provided as PEDs, SEF is also determined for primary energy. Given primary energies are assumed to be used as industrial steam. The SEFs and deriving GHG emissions are evaluated in two cases: electricity, heat and primary energy required for processes is produced either from biogas and other renewables or by the Finnish average energy production.

5.7 Overview of energy consumptions

Table 5.13 presents compiled data of energy consumption and savings from main processes, auxiliaries and applications. In the calculations, the presented values of main, optional and auxiliary processes are converted, when required, to primary energy using primary energy factors, PEFs (Table 5.10), and to GHG emissions using specific emissions factors, SEFs (Table 5.12).

Table 5.13 Compiled energy consumption and saving data from each process and application included in the calculations.

Process	***Technology***	***Energy carrier***	***Unit***	***Energy consumption***	
	Main processes			*Scientific*	*Commercial*
Solid-liquid separation	*Decanter centrifuge*	*Electricity*	*kWh/t*	1.8	3.5
	Screw press	*Electricity*	*kWh/t*	0.4	0.9
Composting	*Windrow composting*	*Electricity*	*kWh/t*	10	18
Thermal drying	*Not specified*	*Heat + Electricity*	*kWh/t_w*[I]	830 + 8.5	970 + 9.6
Pelletizing	*Not specified*	*Electricity*	*kWh/t*	150	240
Ammonia stripping	*Steam stripping*	*Heat*	*kWh/kg_N*	31 *PED*	125 *kWh/t*
	Auxiliary processes				
Pumping	*Normal*	*Electricity*	*kWh/t*	0.35	
	To effluent treatment	*Electricity*	*kWh/t*	0.7	
Conveyance	-	*Electricity*	*kWh/t*	0.28	
Transportation	*Trailer truck, 20 km*	*Diesel*	*kWh/t*	3.4	
Spreading	*Deep fertilizing*	*Diesel*	*kWh/kg*	*N:* 0.5 *P:* 3.8 *or* 8.0	
Effluent treatment	*WWTP*	*Electricity*	*kWh/t*	1	
	Optional main process				
Chemical hygienization	*Chemical*	*PED*	*kWh/t*	-60.5 (8.8[II])	
	Applications				
Land applications	*N-fertilizer substitute*	*PED*	*kWh/kg_N*	-(10.8 + 0.12)	
	P-fertilizer substitute	*PED*	*kWh/kg_P*	-(2.2 + 2.2)[III]	
	Peat substitute	*PED*	*kWh/kg*	0.058[IV]	
Energy production	*Solid fuel*	*PED*	*kWh/kg*	*V*	

I *kWh per tonne water vaporized*
II *Full methane production improvement by thermal hygienization*
III *40 % or 85 % of P in digestate is considered substituting synthetic P (Section 5.3.1)*
IV *1 tonne of digestate substitutes 0.2 tonne of peat*
V *Dependent on digestate moisture and ash content*

5.8 Digestate properties

Since the scope of this Thesis is to evaluate digestate processing using latest technology in operational environment of Finland, in calculations the digestate is residue of wet AD process. According to Partanen (2010) only one pilot biogas plant in Finland featured dry AD process in 2010. The standard hygienization and chemical treatment are assumed to provide pathogen free digestate. Also, in Finnish digestates amounts of other impurities are generally below the limits, and thus, the pathogens and impurities are ignored in the property follow-up. Additionally, the chemicals added in the processes are not taken into account.

The properties of raw digestate used in the calculations are provided as arithmetic average values by the digestate quality research of around 1,800 samples by EBA, cited by Fachverband Biogas et al. (2013). In the end, the 10th and 90th percentile values of the same study are examined to determine whether they affect the process balances. The discussed values are presented in Table 5.14. As seen, DM content varies between 3 and 9 %, proving popularity of wet fermentation in Europe.

Table 5.14 Properties of raw digestates in European analysis of around 1,800 samples performed 2009 – 2012 (EBA cited by Fachverband Biogas et al. (2013)).

Value	*DM (%)*	*ODM of DM (%)*	*N of DM (%)*	*NH_4-N of DM (%)*	*P of DM (%)*
10th percentile[I]	2.7	55.2	4.9	1.6	1.9
Arithmetic average	5.7	69.3	10.4	6.0	3.8
90th percentile[I]	9.1	82.4	18.1	12.6	5.5

I *10th percentile indicates that 10 percent and 90th that 90 percent of the observed values are found below the value*

5.8.1 Solid-liquid separation

No data was found on relation of dry matter or nutrient separation efficiency and energy consumption of mechanical separation devices. Møller et al. (2007) have found correlations between DM content of raw digestate and the mass, DM content and nutrients in solid fraction, which, however, have been ignored in this study due to limited sampling and weak coefficient of determination. Thus the properties of solid and liquid fractions are determined by typical percentages of compound divisions. For decanter centrifuge, the data is provided by Jørgensen, cited by Al Seadi et al. (2013b), and for screw press after Bauer et al. (2009). The percentages used in the calculations, are presented in Table 5.15. In the energy value calculations, the ash content is considered as the non-organic part of DM.

Table 5.15 Division of components into solid and liquid fractions in decanter centrifuges (Wesnæs, et al., 2013) and from combined data of screw press and screen separator (Bauer, et al., 2009).

		Mass %	*DM %*	*ODM[I] %*	*N_{tot} %*	*NH_4-N %*	*P_{tot} %*
Decanter centrifuge	*Solid fraction*	12	63	47[II]	25	20	72
	Liquid fraction	88	37	53[II]	75	80	28
Screw press	*Solid fraction*	21	62	56	31	23	52
	Liquid fraction	79	38	44	69	77	48

I *Ash is considered the non-organic part of DM*

II (DANETV, 2010)

5.8.2 Composting

In composting the organics loss is assumed to be 50 % and water loss 80 % (Rehl & Müller, 2011). Also, due to temperature rise, 20 % of ammonium is assumed to be emitted to air as NH_3. The designation list of fertilization products in Finland (Evira, 2013b), requires organic content of minimum 25 % of dry matter, when the matter derives entirely or partly from digestate. This requirement is, however, ignored since mixing to additive organic matter is not considered to generate extra energy consumption.

5.8.3 Drying and pelletizing

In this study, the decrease of water content is assumed to be directly proportional to the thermal energy used and, thus, LHV required. Level of 10 % is used in the calculations. Also ammonium is lost in thermal drying: In the study by Maurer & Müller (2012) the ammonium loss of 91.7 % was observed during drying from DM content of 27 % to 92 %. Value of 90 % is used in the calculations. No information was found on changes of other properties but density during pelletizing. Since the quantity of the matter is monitored by mass and the density of digestate products is assumed to be roughly equal, around 1000 kg m^{-3} (Käytännön maamies, 2012) (Kratzeisen, et al., 2010), the density is assumed to be irrelevant in e.g. transportation. Similarly to Kratzeisen et al. (2010) use of binding agent in pelletizing is ignored.

5.8.4 Ammonia stripping

In ammonia stripping, only ammonia is considered to be extracted from the liquid digestate. The water vaporized is considered equivalent to steam input (Sauramo, 2009). Thus, the water content of effluent remains the same as in the liquid fraction and the water in ammonia stream is equal to steam input. Steam input is determined to cover 64 % of ammonium sulphate solution as the DM content is, according to Piccinini et al. (2013), 36 %. Table 5.16 presents ammonium, DM and total nitrogen of DM content in ammonium sulphate solution and rate of ammonium recovery in scientific and commercial sources.

Table 5.16 Dry matter, ammonium in total nitrogen and total nitrogen in DM content in ammonium sulphate solution and rate of ammonium recovery in ammonia stripping according to study by Piccinini et al. (2013).

Feature	*Unit*	*Value*
NH_4-N of N_{tot} in $(NH_4)_2SO_4$ solution	*%*	90
DM content in $(NH_4)_2SO_4$ solution	*%*	36
N_{tot} of DM in $(NH_4)_2SO_4$ solution	*%*	20
NH_4-N recovery	*%*	68

5.8.5 Liquid fertilizer chain

Liquid fraction of solid-liquid separation is used as such. Thus, the properties are determined directly by the division of properties in the separator device as presented in Table 5.15.

6 APPLICATION CHAIN CALCULATIONS

This Chapter presents the main energy and GHG emission calculations of the study and results for the separate application chains, which also are analyzed. The values, including energy data, emission factors and digestate properties in processes, are provided in the previous Chapter and linked in chains for the four end products: soil improver-growing media, solid fuel (fertilizer pellet), ammonium sulphate fertilizer and liquid fertilizer. The energy balances are determined in unit kilowatt hours per tonne raw digestate and GHG emissions in kilograms CO_2 equivalents, by GWP 100, per tonne raw digestate.

6.1 Calculation tool

As a secondary object of this Thesis, an excel-based calculation tool was developed to improve data processing and comparison of the results. The tool counts simultaneously changes in digestate properties to energy use and GHG emissions in the application chains: from raw digestate, the untreated residue of anaerobic digestion process to the application of end product. Energy uses and GHG emissions are usually provided in relation to the mass of the matter treated while in land applications the amounts of nutrients determine the output values; thus follow-up of the digestate properties is essential as the processes are linked. The relevant properties monitored are contents of mass, water, dry matter, organics, nitrogen, ammonium and phosphorous. Operation and result tab of the tool is presented in Figure A3.1 of Appendix 3.

The hygienization and solid-liquid separation are included in each chain. Hygienization, however, is considered as an optional main process, since the benefits of chemical hygienization are doubtful, as discussed in Section 5.2.1. Separation, instead, is the central process of digestate treatment and may be performed by either decanter centrifuge or screw separator. After the separation, two chains derive from solid fraction and two from liquid, as seen in Figure 5.1. The energy consumptions of solid-liquid separation and pumping or raw digestate are included in the specific chains without allocating to solid and liquid fractions. Between each main process, either pumping or conveyance is applied while the final products are transported to application site and, in cases of land use, spread on fields. Generally, the energy use of pumping, conveyance or transportation is considered in the previous main process. As exceptions, the pumping of raw digestate is included in the solid-liquid separation, transportation of liquid fertilizer is included in the application and spreading is always included in the application. Also, drying and ammonia stripping generate effluent which is considered to be pumped and treated in a WWTP.

The energy demands of main and auxiliary processes are converted to primary energies, when provided as secondary energies, using primary energy factors, PEFs (Table 5.10), and to GHG emissions using specific emissions factors, SEFs (Table 5.12). The scientific and commercial sources are applied for main processes, except for chemical hygienization. The primary energy and GHG savings from replacing synthetic fertilizer and peat production by land application are determined by factors provided in Tables 5.9 and 5.11, respectively. In the solid fuel application, the GHG emission savings are estimated to derive form average Finnish energy production.

The GHG emissions from heat, electricity and primary energy uses are by standard estimated to derive from the Finnish average energy production and in an extra case from renewable energy production. As determining the area fertilized and the amount of synthetic P-fertilizer substituted, related energy balance and emissions per kilogram of phosphorous, the digestates are categorized in matters containing sewage sludge origin digestate and other digestates.

6.1.1 Reference path (RP) and special option (SP)

To improve determination and comparison of different process paths, in which e.g. chemical hygienization or the two solid-liquid separators are applied, the reference case is determined. The reference chain is assumed to represent the generic and preferred path in Finland, against which the more special options can be set. The options chosen for the *reference path (RP)* are:

- Chemical hygienization is ignored due to doubtful applicability and benefits
- Decanter centrifuge is used for solid-liquid separation due to high efficiency
- Digestate partly or entirely sewage sludge origin due to popularity in Finland

Performing the calculations, the digestate deriving from other origin but sewage sludge was observed to systematically increase energy consumptions in land applications. This is due to higher energy consumption of phosphorous based digestate spreading than energy savings generated by synthetic P-fertilizer substitution. The more phosphorous available, the more energy used. Due to similar energy consumption increase in each land application path, the comparison of effects of other origin digestate is not considered reasonable and is ignored in the main calculations. However, the effects of availability will be evaluated in Section 6.3.1. Also, chemical hygienization is observed separately, in Section 6.3.2, as it is not considered to affect the digestate properties. The energy savings of chemical hygienization and full methane production improvement are then compared to determine whether the influence on overall energy balance is noteworthy or not.

In the calculations and tables of next section, the reference path is compared to the special option of screw press usage *(SP)*. The screw press alters division of each observed compound and thus affects the processes remarkably. The changes in mass, DM content and nutrient divisions obviously influence the energy consumptions of processes and energy savings of applications.

6.2 Energy efficiencies and GHG emissions

The energy efficiencies and greenhouse gas emissions are determined for each of the four end product chains in the reference path, RP, and the special option, SP. The units of PEDs in the final results are kilowatt hours per tonne raw digestate and of emissions kilograms CO_2 equivalents per tonne. Energy consumption occurs in the main and auxiliary processes and energy savings in end product applications as e.g. production of synthetic fertilizers is avoided. Each chain starts from raw digestate, the untreated residue of anaerobic digestion process, and ends in the application of end product. The process specific energy demands and savings in RP and SP are presented in Figures A4.1 – A4.16 of Appendix 4.

GHG emissions derive from energy demands and savings, except for synthetic fertilizer and peat replacement, which are determined by emissions from their production, provided in Table 5.9. The GHG emissions deriving from heat, electricity and primary energy are by standard estimated to base on the Finnish average energy production. For commercial energy values, the emissions are in an additional case estimated as deriving from biogas combustion. The energy content of solid fuel is considered in both cases to substitute the Finnish average energy production emissions. The biogas use is not included in the energy calculations. The process specific greenhouse gas emissions in RP are presented in Figures A5.1 – 5.12 of Appendix 5.

6.2.1 Soil improver-growing media

Composting is the application specific main process of the processing chain of multifunctional soil improver-growing media (SIGM) as illustrated in Figure 6.1. Division into optimum and standard values is applied for solid-liquid separation and composting processes. The energy savings are generated by peat, P- and N-fertilizer substitution while the rest of the processes consume energy. The energy use of spreading bases on area limit of phosphorous use.

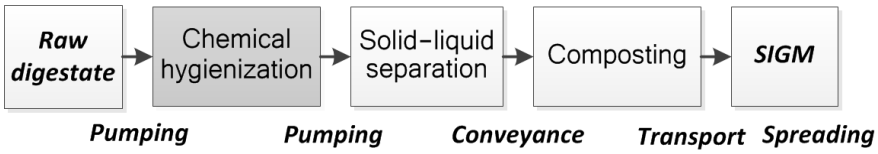

Figure 6.1 The process chain of soil improver-growing media (SIGM) application. Chemical hygienization is excluded from calculations of this section but will be discussed in Section 6.3.2.

The results of energy and emission calculations for the SIGM chain in RP and SP are shown in Table 6.1 while the process specific energy consumptions are presented in Figures A4.1 – A4.4 of Appendix 4. With optimal values, the energy balance in RP is slightly positive (i.e. energy is saved) while standard values result in small energy demand, due to difference of few kilowatt hours in both mechanical separation and composting. As observed in the figures, comparing SP to RP, the energy saving in separation is compensated by higher composting energy, which is a result of 75 % increase in solid fraction mass after screw press. However, due to lower phosphorous content, the diesel use of spreading decreases and the higher nitrogen content increases replacement of synthetic nitrogen production. Consequently, energy savings of 8.9 and 4.6 kWh per tonne raw digestate are generated using optimum and standard values in SP, respectively. While most of the auxiliaries are unsubstantial, the energy demand of phosphorous based spreading is noteworthy, 6 to 8 kWh, which applies to fertilizer pellet as well.

Figures A5.1 – A5.3 of Appendix 5 present process specific GHG emissions in RP for the application chain of SIGM. As a result of strong dependence on fertilizer and peat production substitution, the GHG emissions of SIGM chain are high but notably even between the use of optimum and standard values, which only change the energy demands of processes. Therefore, neither the usage of renewable energy in processing lowers the emissions substantially. The lower emissions of SP than RP

derive from higher nitrogen content and mass after screw press usage, the latter of which generates avoidance of peat production.

Table 6.1 Primary energy demand and GHG emissions in the processing paths of soil improver-growing media (SIGM). Total energy uses of solid-liquid separation and raw digestate pumping are included while chemical hygienization is excluded.

Feature	*Unit*	*Value class*	*RP*	*SP*
PED	*kWh/$t_{digestate}$*	*Optimum*[I]	-2.8	-8.9
		Standard[II]	2.5	-4.6
GHG emissions	*kg CO_2-eq/$t_{digestate}$*	*Optimum*[I]	-15.8	-20.6
		Standard[II]	-15.2	-20.1
		Standard (renewable)[III]	-16.6	-21.2

I *Scientific sources for energy use values in the main processes*
II *Commercial sources for energy use values in the main processes*
III *Heat, electricity and primary energy produced from biogas or other renewables instead of the Finnish average*

6.2.2 Solid fuel (fertilizer pellet)

In the processing chain of solid fuel digestate which may also be used as fertilizer pellet, thermal drying and pelletizing are the chain specific main processes, as seen in Figure 6.2. Scientific and commercial sources are applied for solid-liquid separation, drying and pelletizing. When the product is applied as solid fuel, the energy content of the matter, which is determined as a product of mass and lower heating value, is considered to generate primary energy savings. As fertilizer pellet, the nitrogen and phosphorous content save energy from synthetic fertilizer production. The rest of the processes demand primary energy.

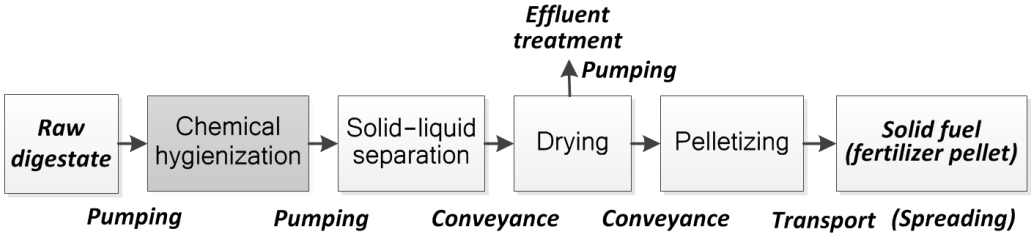

Figure 6.2 The process chain of solid fuel (fertilizer pellet) application. Chemical hygienization is excluded from the calculations of this section but will be discussed in Section 6.3.2.

Energy demand and GHG emissions of solid fuel and fertilizer pellet chains are seen in Tables 6.2 and 6.3. Energy use of the fertilizer pellet chain is found remarkably high compared to solid fuel application due to lower energy value in fertilizer substitution. The process specific energy consumptions for solid fuel chain are presented in Figures A4.5 – A4.8 of Appendix 4 and GHG emissions for RP in Figures A5.4 – A5.6 of Appendix 5. The charts for fertilizer pellet chain would be similar, except for the application.

Table 6.2 Primary energy demand and GHG emissions in the processing paths of solid fuel. Total energy uses of solid-liquid separation and raw digestate pumping are included while chemical hygienization is excluded.

Feature	*Unit*	*Value class*	*RP*	*SP*
PED	*kWh/$t_{digestate}$*	*Optimum*[I]	-7.2	70.0
		Standard[II]	18.2	110.0
GHG emissions	*kg CO_2-eq/$t_{digestate}$*	*Optimum*[I]	-2.4	4.1
		Standard[II]	0.15	7.9
		Standard (renewable)[III]	-12.4	-14.8

I *Scientific sources for energy use values in the main processes*
II *Commercial sources for energy use values in the main processes*
IIII *Heat, electricity and primary energy produced from biogas or other renewables instead of the Finnish average*

Table 6.3 Primary energy demand and GHG emissions in the processing paths of fertilizer pellet. Total energy uses of solid-liquid separation and raw digestate pumping are included while chemical hygienization is excluded.

Feature	*Unit*	*Value class*	*RP*	*SP*
PED	*kWh/$t_{digestate}$*	*Optimum*[I]	102.2	196.9
		Standard[II]	127.6	236.8
GHG emissions	*kg CO_2-eq/$t_{digestate}$*	*Optimum*[I]	2.4	8.9
		Standard[II]	4.9	12.7
		Standard (renewable)[III]	-7.7	-10.0

I *Scientific sources for energy use values in the main processes*
II *Commercial sources for energy use values in the main processes*
III *Heat, electricity and primary energy produced from biogas or other renewables instead of the Finnish average*

The reference path of solid fuel chain generates primary energy saving of 7.2 kWh in optimal case and in standard case energy use of 18.2 kWh per tonne raw digestate. The high energy demand of thermal drying, down to moisture content of 10 %, is compensated by LHV of 10.4 MJ kg^{-1}. If screw press is used, the water content of solid fraction is higher and, thus, more energy is required in thermal drying. As a result, the LHV of 12.6 MJ kg^{-1} does not cover the energy demand of 220 kWh in standard conditions and 190 kWh in optimal, per tonne raw digestate. LHV of over 10 but under 15 MJ kg^{-1} reaches status of class 4 solid recovered fuel, as seen in Appendix 2. With optimal values PED of 70 kWh and with standard 110 kWh per tonne raw digestate is achieved in SP of solid fuel chain. As seen in Table 6.3, the energy value of fertilizer pellet application is in RP ca. 110 kWh and in SP ca. 130 kWh lower than of solid fuel. The energy savings are minor since most of the ammonium is volatized and, thus, half of the nitrogen is lost in the thermal drying.

With optimal values, 2.4 kg CO_2 equivalents of GHG emissions are saved in RP per tonne digestate while standard values result in near-zero emission generation due to higher energy consumptions, as seen in Figures A5.4 – A5.5. If the process energy is produced from renewable sources, mechanical separation, thermal drying and pelletizing generate zero emissions (except for transportation), the saving of 12.4 kg CO_2 equivalents derives from substitution of Finnish average energy production. After screw press the GHG savings are even higher due to greater LHV. The GHG balance of fertilizer pellet is observed to be around 4 – 5 kg CO_2 equivalents worse in different processing paths compared to solid fuel.

6.2.3 Ammonium sulphate fertilizer

Ammonium sulphate fertilizer differs from other applications since the product is separated from the "main stream" in ammonia stripping and the effluent is pumped to treatment in WWTP. In solid-liquid separation and ammonia stripping energy uses are provided from scientific and commercial sources. The ammonium sulphate fertilizer does not contain phosphorous: the area of spreading is determined by the nitrogen content. Substitution of N-fertilizer production generates energy savings while the processes demand energy. The process chain is illustrated in Figure 6.3.

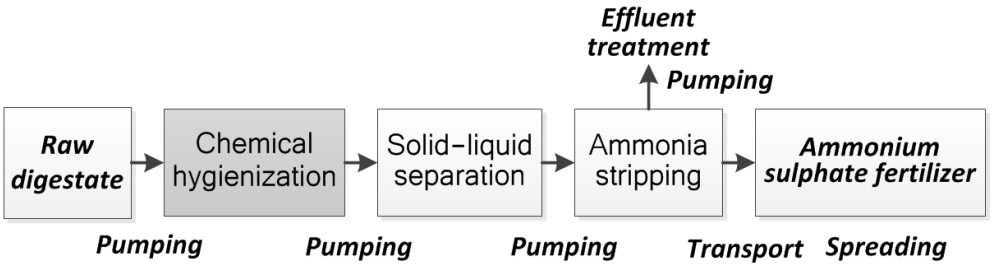

Figure 6.3 The process chain of ammonium sulphate fertilizer. Chemical hygienization is excluded from the calculations of this section but will be discussed in 6.3.2.

The PEDs and GHG emissions in RP and SP of ammonium sulphate fertilizer chain are shown in Table 6.4. while the process specific PEDs are presented in Figures A4.9 – A4.12 of Appendix 4 and GHGs in Figures A5.7 – A5.9 of Appendix 5. The energy demand in the ammonium sulphate fertilizer chain is clearly higher compared to other chains, except for fertilized pellet. This is due to major energy consumption of ammonia stripping process, which cannot be covered by nitrogen content of the fertilizer solution. With optimum values, SP reaches lower PED than RP as the nitrogen content of liquid fraction is lower after screw press: the energy demand of stripping is determined by kilograms nitrogen recovered while its energy use is higher than fertilizer substitution per kg nitrogen. Using standard values, the similar result is reached due to lower dewatering efficiency of screw press as the energy use of ammonia stripping, defined in the commercial source, is determined by the mass of liquid fraction.

As for GHG emissions, the nitrogen content of ammonium sulphate solution generates great savings. Despite the high energy demands, the GHG balance results in avoidance of 9.0 and 3.5 kg CO_2 equivalent emission in optimal and standard conditions in RP,

respectively. In SP, the savings are slightly higher due to lower energy consumption in ammonia stripping whereas the usage of renewable energy for the stripping causes greater benefit for RP due to higher nitrogen content of the product.

Table 6.4 Primary energy demand and GHG emissions in the processing paths of ammonium sulphate fertilizer. Total energy uses of solid-liquid separation and raw digestate pumping are included while chemical hygienization is excluded.

Feature	*Unit*	*Value class*	*RP*	*SP*
PED	*kWh/$t_{digestate}$*	*Optimum*[I]	60.7	49.7
		Standard[II]	136.9	117.2
GHG emissions	*kg CO_2-eq/$t_{digestate}$*	*Optimum*[I]	-9.0	-9.7
		Standard[II]	-3.5	-4.8
		Standard (renewable)[III]	-18.0	-17.3

I *Scientific sources for energy use values in the main processes*
II *Commercial sources for energy use values in the main processes*
III *Heat, electricity and primary energy produced from biogas or other renewables instead of the Finnish average*

6.2.4 Liquid fertilizer

The liquid fertilizer is applied to land directly after solid-liquid separation, as seen in Figure 6.4. Thus, the energy demand is generated by the base processes; solid-liquid separation and auxiliaries while the energy savings derive from the substitutions of N- and P-fertilizer productions. Also the division into scientific and commercial sources is applied only in solid-liquid separation. Due to importance of mechanical separation, comparison of RP and SP is especially interesting. Chemical hygienization is excluded from the calculations of this section but will be discussed later.

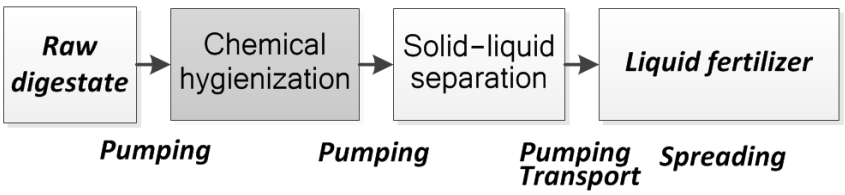

Figure 6.4 The process chain of liquid fertilizer. Chemical hygienization is excluded from the calculations of this section but will be discussed in 6.3.2.

Table 6.5 shows PEDs and GHG emissions in RP and SP of liquid fertilizer chains. The energy and GHG savings are generated with both optimum and standard values in the reference path and in the special option of screw press use. The energy balances of RP and SP are similar since the energy saving of screw press is compensated with lower nutrient content, as seen in Figures A4.13 – A4.16 of Appendix 4. With the optimal energy use, decanter centrifuge generates energy saving of 36.8 kWh for the chain, which is slightly higher than of screw press. As for standard values, the screw press use results in a bit higher saving than RP; 33.8 kWh per tonne raw digestate. Transportation and spreading generate notable PED of 7 to 9 kWh.

The strong dependency on nitrogen content applies also to GHG emissions, which are presented in detail in Figures A5.10 – A5.12 of Appendix 5. Similarly to SIGM chain, the GHG emissions are high but notably even between the paths. The use of renewable energy for the production of process energy generates rise of only 3 % in the saving of GHG emissions in RP. The use of decanter centrifuge results in 2.4 to 3.1 kg (6 to 8 %) greater avoidance of CO_2 equivalent emissions than screw press.

Table 6.5 Primary energy demand and GHG emissions in the processing paths of soil improver-growing media (SIGM). Total energy uses of solid-liquid separation and raw digestate pumping are included while chemical hygienization is excluded.

Feature	*Unit*	*Value class*	*RP*	*SP*
PED	*kWh/$t_{digestate}$*	*Optimum*[I]	-36.8	-34.8
		Standard[II]	-33.5	-33.8
GHG emissions	*kg CO_2-eq/$t_{digestate}$*	*Optimum*[I]	-38.1	-35.4
		Standard[II]	-37.7	-35.3
		Standard (renewable)[III]	-38.7	-35.6

I *Scientific sources for energy use values in the main processes*
II *Commercial sources for energy use values in the main processes*
III *Heat, electricity and primary energy produced from biogas or other renewables instead of the Finnish average*

6.3 Separate factors

6.3.1 Availability of phosphorous

If the digestate derives entirely from other origin but sewage sludge and thus represents a special option in this study, 85 % of the phosphorous content, as recommended by Marttinen et al. (2013), is considered in the substitution of synthetic P-fertilizer and determination of fertilization area. For sewage sludge origin digestate the corresponding share is 40 %. The increase in applicability of phosphorous raises the area of spreading, which was observed to consume more energy than synthetic P-fertilizer substitution. Since the rise in energy consumption is directly proportional to phosphorous content, comparison of the two cases is performed separately in this section.

In RP, the 85 % applicability causes ca. 5.8 kWh rise in energy consumption in land application chains of solid fraction and ca. 2.3 kWh rise in liquid fertilizer chain, per tonne raw digestate. In SP the increases are respectively ca. 4.2 kWh and 3.9 kWh, due to more even split of phosphorous in the screw press separation. These values may be considered fairly low since the substitution of N-fertilizer generates savings of 14.5 – 47.8 kWh per tonne raw digestate. As for GHG emission, the substitution of synthetic P-fertilizer use overrides amount of CO_2 equivalent emissions produced by digestate spreading. Thus, the increase in phosphorous content saves, but only a non-existent quantity, of GHG emissions.

6.3.2 Chemical hygienization

Chemical hygienization is evaluated separately from the chain calculations since it is not considered to alter digestate properties and due to uncertainty in sanitation efficiency and energy balance values, as discussed in Section 4.1. According to Luste & Luostarinen (2010) the thermal pre-hygienization could improve methane productivity of AD process over energy consumption benefit of chemical hygienization, because of which the energy saving potential of chemical hygienization is doubtful.

The scale of optimal energy saving of chemical hygienization and maximum energy loss due to full increase of methane production by thermal pretreatment is presented in Table 6.6. Comparing to energy balances of the applications chains discussed in Sections 6.2.1 – 6.2.4, the possible energy saving could be significant, nearly 60 kWh per tonne digestate. However, the potential improvement of methane productivity may override the saving and, thus, the chemical hygienization could, in the worst case, consume nearly 10 kWh of extra energy. The GHG emissions derive from and follow the PEDs.

Table 6.6 Primary energy savings and demands in chemical hygienization with options of full energy saving compared to thermal pretreatment and full benefit loss of methane production increase by thermal pretreatment.

Feature	*Unit*		*Value*
PED	*kWh/$t_{digestate}$*	*Full energy saving*	-59.7
		Full methane production[I]	9.6
GHG emissions	*kg CO_2-eq/$t_{digestate}$*	*Full energy saving*	-6.6
		Full methane production[I]	1.1
		Renewable[II]	0

I *Possible methane production increase of thermal hygienization added to energy saving of chemical hygienization*

II *Heat, electricity and PED produced from biogas or other renewables*

6.3.3 Energy recovery

Heat consumed in the processes (hygienization, ammonia stripping and drying) is considered as industrial steam in this study. In the calculations, this heat is converted to PED using the Finnish average primary energy factor of industrial steam (1.27) when it is produced from biogas (1.05): 1.33. However, if the heat is considered as waste heat of e.g. biogas combustion after power production or recycled from or to other heat requiring processes, the PEF could be decreased as a result of energy recovery. For example, the PEF of district heat from CHP by energy allocation is determined by Keto (2010) to be 0.98 – 1.06. If the PEF of 1.33 was lowered to 1.00 by energy recovery, the PED of a process would decrease by 25 %: since the heat consuming processes feature major energy demand, the energy recovery would have a substantial influence on these chains. For this study, the energy recovery is not discussed further since no scientific or commercial information on the issue was found.

6.3.4 Digestate properties

The digestate properties are monitored due to application chains since the energy and GHG values are dependent on the amounts of different components. The initial digestate is determined by the average values of digestate quality research of around 1,800 samples by EBA, cited by Fachverband Biogas et al. (2013) and shown in Table 5.14. The initial masses of components and the splits in mechanical separation are presented in Table 6.7. Even though the masses of DM and ODM are rather even in the solid fractions after both separators, the water separation, as observed in the total mass, is significantly worse in the screw press. The split of nitrogen is slightly and of phosphorous clearly better in the decanter centrifuge. In terms of energy efficiency, the use of screw press is beneficial for SIGM and ammonium sulphate fertilizer chains. For the first mentioned, this is caused by a higher nitrogen content of solid fraction. As for ammonia stripping, the energy demand is increased by either nitrogen (optimum conditions) or total mass (standard conditions), which are higher in the liquid fraction after decanter centrifuge.

Table 6.7 Monitored components in solid and liquid fractions after solid-liquid separation by decanter centrifuge and screw press. Liquid fraction is spread directly at field in the option of liquid fertilizer application.

Stage		***Mass*** *kg*	***DM*** *kg*	***ODM*** *kg*	N_{tot} *kg*	NH_4-***N*** *kg*	P_{tot} *kg*
Initial		1000	57	39.5	5.9	3.4	2.2
Decanter centrifuge	*Solid fraction*	120	35.9	18.6	1.5	0.68	1.6
	Liquid fraction	880	21.1	20.9	4.4	2.7	0.6
Screw press	*Solid fraction*	210	35.3	22.1	1.8	0.78	1.1
	Liquid fraction	790	21.7	17.4	4.0	2.6	1.1

The masses of components in the end products, except for liquid fertilizer, separated by decanter centrifuge are shown in Table 6.8. As seen, the efficient dewatering results in a great decrease in the masses of end products. Since the nitrogen content is considerably more beneficial for the energy and GHG balances than the phosphorous content, the SIGM chain, despite the low energy consumption of composting, cannot reach savings of liquid fertilizer chain. The high ODM content of solid fuel results in LHV of over 10 MJ kg^{-1} and, thus, a substantial energy benefit. The ammonium sulphate fertilizer is considered to contain only non-organic dry matter and of nutrients only nitrogen.

Table 6.8 Monitored components in the end products after decanter centrifuge, except for liquid fertilizer, which is presented as liquid fraction in Table 6.7.

End product	*Mass kg*	*DM kg*	*ODM kg*	N_{tot} *kg*	NH_4-*N kg*	P_{tot} *kg*
SIGM	43.3	26.5	9.3	1.3	0.54	1.6
Solid fuel (Fertilizer pellet)	39.2	35.3	18.6	0.86	0.07	1.6
Ammonium sulphate fertilizer	28.5	18.3	0	2.1	1.8	0

6.3.4.1 Alteration of raw digestate properties

Since the properties of raw digestate may vary broadly and the PED and GHG emission of application chains are highly dependent on e.g. nutrient and ODM contents, the property alterations were examined separately from the main study. The component contents of raw digestate for the property test derive from 10th and 90th percentile values of the same quality research, from which the average values were drawn for the main calculations. Table 6.9 presents the effect of property alterations for the solid fuel and liquid fertilizer chains, the latter representing the land applications, in optimum conditions in RP.

As seen, the property alterations influence the energy efficiency of solid fuel more than of liquid fertilizer. The low water and high organics content of 90th percentile values decrease the energy demand of thermal drying while the energy content of solid fraction is increased. Although the risen nutrient content of liquid fertilizer does not beat the energy savings of solid fuel, higher GHG savings are generated mainly due to synthetic nitrogen fertilizer substitution. Compared to PED values reached with the average properties of raw digestate, the 10th percentile results in rise of 88.0 kWh per tonne raw digestate in solid fuel chain and of 35.6 kWh in liquid fertilizer chain. With 90th percentile values, the respective PED decreases are 121.9 and 83.3 kWh while GHG emissions lower by 12.9 and 70.7 kg CO_2 equivalents per tonne raw digestate. As expected, the digestate properties are essential for the energy and GHG balances.

Table 6.9 The influence of altering digestate properties to 10th and 90th percentile values (Table 5.14) of the study by EBA (Fachverband Biogas, et al., 2013) on the properties, PED and GHG emissions of solid fuel and liquid fertilizer in optimal conditions in RP.

Stage		*Mass kg*	*DM kg*	*ODM kg*	N_{tot} *kg*	NH_4-*N kg*	P_{tot} *kg*	*PED kWh/t*	*GHG* $kg_{CO2\text{-}EQ}/t$
10th percentile	*Solid fuel*	18.8	16.9	7.0	0.25	0.008	0.36	80.8	6.77
	Liquid fertilizer	880	10.0	7.9	1.0	0.32	0.14	-1.18	-7.40
90th percentile	*Solid fuel*	61.4	55.3	35.3	2.1	0.23	3.6	-129.1	-15.3
	Liquid fertilizer	880	33.7	39.8	12.4	9.2	1.4	-120.1	-108.9

7 SUMMARY OF RESULTS AND SENSITIVITY ANALYSIS

The results of energy efficiency and GHG calculations presented in the previous sections are summed up in this chapter. The energy efficiencies and GHG emissions of the observed application chains are compared to each other in terms of optimal and standard values. Also the sensitivity of results is analyzed to measure the possible margins of errors for the values.

7.1 Energy efficiency

In terms of energy balance, the highest primary energy savings are reached by the liquid fertilizer application, as seen in Figures of optimal PEDs 7.1 and standard PEDs 7.2. The generated savings derive from substitution of synthetic fertilizer production, mainly nitrogen, while energy is used only for auxiliaries and solid-liquid separation. Thus, also the variance between optimal and standard values, which affects only the main processes, is minor. In SIGM chain, the energy demand of composting, an extra procedure compared to liquid fertilizer chain, is low but the decreased nitrogen content of solid fraction results in clearly lesser savings. While the energy savings of liquid fertilizer chain set between 33.8 and 36.8 kWh per tonne raw digestate, the values for SIGM chain vary from saving of 8.9 kWh to demand of 2.5 kWh. The energy benefit of optimal values in RP, compared to the standard, is for the first mentioned low, 3.3 kWh, as well as for the latter, 5.3 kWh.

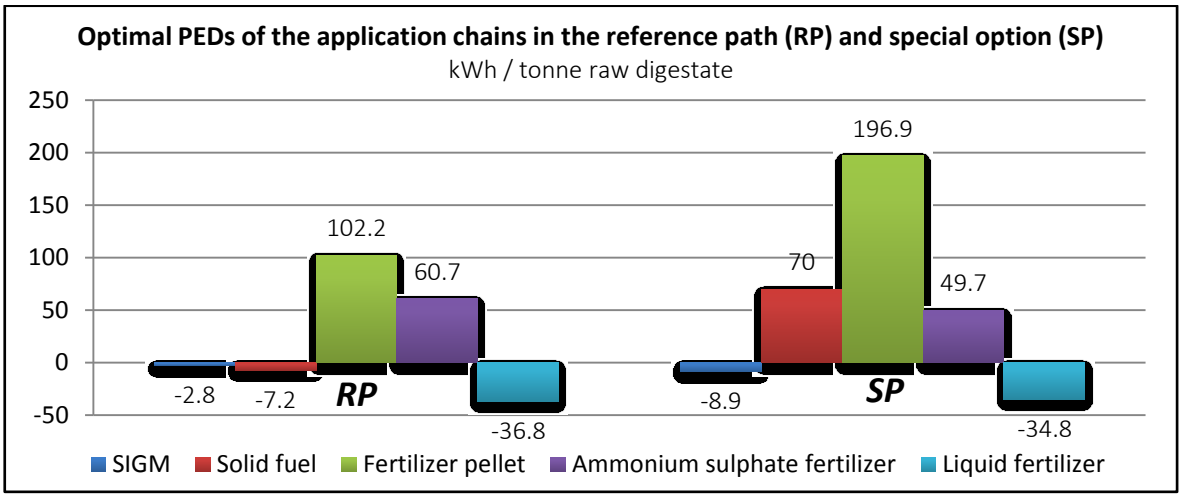

Figure 7.1 Comparison of optimal PEDs in RP and SP of each application chain.

As determining the best energy value for the entire digestate treatment procedure, the liquid fraction should be used directly after screw press separation as liquid fertilizer and the solid fraction should be applied either as SIGM or solid fuel. With optimal energy uses of decanter centrifuge (in RP), thermal drying and pelletizing, the solid fuel application results in a slightly higher primary energy saving than SIGM chain, 7.2 kWh per tonne raw digestate. However, the standard values raise the energy demand notably, to 18 kWh while the screw press (in SP) is obviously unsuitable for solid fuel production with PED demand up to 110 kWh.

The highest energy demand is generated when, instead of solid fuel, the pelletized digestate is used as fertilizer pellet, from which half of the nitrogen is volatized as ammonia in thermal drying. Also, considering the energy demand, the ammonium sulphate fertilizer application is unfavorable as the PED varies between 49.7 and 136.9 kWh per tonne raw digestate. The energy calculations are obviously adverse for the chain since increase of nitrogen recovery raises the energy demand of stripping more than energy benefit of N-fertilizer substitution. Thus, the screw press use, resulting in low nitrogen content in liquid fraction, causes decrease in energy demand.

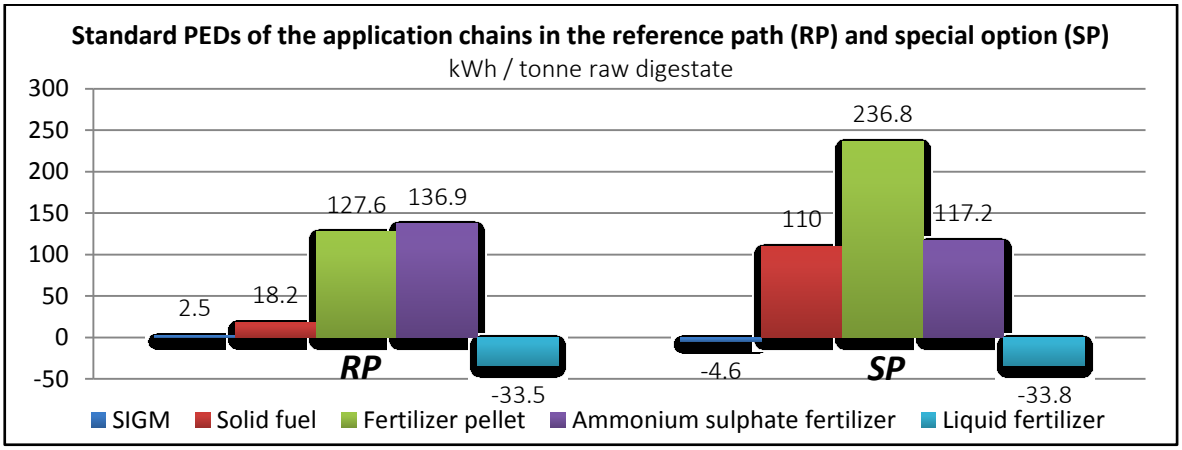

Figure 7.2 Comparison of standard PEDs in RP and SP of each application chain.

According to the gas yield table by SEAI (2010), one tonne cattle dung, chicken litter, MSW and sewage sludge generate from 270 to 740 kWh of biogas. Thus, the energy demands in the applications chains of especially fertilizer pellet and ammonium sulphate fertilizer seem to account for a substantial share of energy generation in the whole biogas process. On the other hand, the energy savings produced by applying solid fraction as SIGM and liquid directly as fertilizer would raise the total energy benefit noteworthy. Studying the auxiliaries, energy demand of phosphorous based spreading, 3 to 8 kWh, and transportation of liquid fertilizer over 20 km, 4 kWh, are noteworthy. Also, the values are volatile since altering the spreading area and the transportation distance would affect the energy demands directly.

7.1.1 Comparison to the study by Rehl & Müller (2011)

In one of the only and probably the most extensive LCA researches on digestate applications by Rehl & Müller (2011), the application chains end up in PEDs of ca. -30 kWh (0.1 MJ per kg) to 360 kWh (1.3 MJ per kg) per tonne raw digestate treated. However, PEFs, the set-ups of processing paths as well as the process and application specific energy values differed from this study. The highest demand is produced by a chain of thermal drying of whole digestate, after which the product is applied to land as pellet: the result is parallel to the fertilizer pellet chain of this study, as PED up to 236.8 kWh is generated. The difference can be assumed to derive from lack of mechanical separation in the chain of Rehl & Müller. The greatest savings in the referred study occur in three chains: 1. Direct land application of the whole digestate. 2. Composting and applying the solid fraction to land while liquid is applied directly after separation. 3. Similar to previous but instead of composting, the solid fraction is

dried by solar dryer. The saving of 30 kWh is well correspondent to the results of this study, as the liquid fertilizer generates saving of ca. 33 – 37 kWh and the energy balance of the SIGM chain is near to zero.

7.2 Greenhouse gas emissions

Similarly to energy efficiency values, the highest GHG savings are generated by liquid fertilizer and SIGM chains, values of which are rather even between the optimal and standard conditions, as shown in Figures 7.3 of optimal values, 7.4 of standard values and 7.5 of standard values with the renewable energy application. Low energy demands of processing and high nitrogen contents result in savings of 35.3 – 38.7 kg CO_2 equivalents per tonne raw digestate for the first mentioned and 15.8 – 21.2 kg CO_2-eq for the latter. The highest savings are generated, naturally, in the case of renewable heat, electricity and PED production for processing.

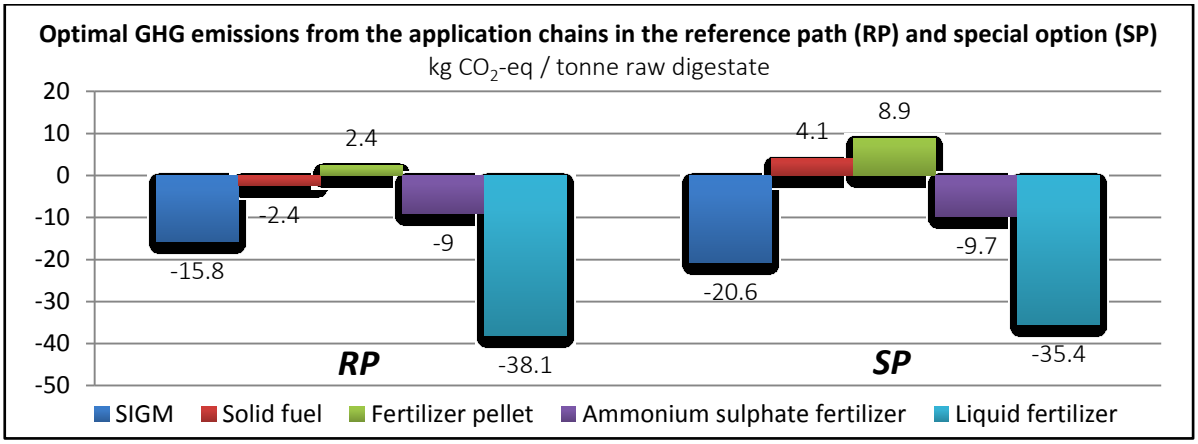

Figure 7.3 Comparison of optimal GHG emissions in RP and SP of each application chain.

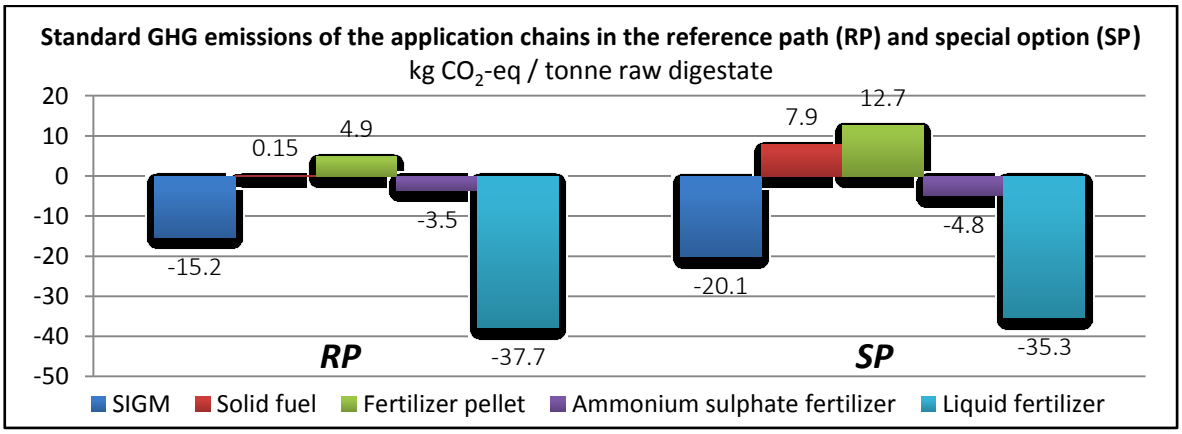

Figure 7.4 Comparison of standard GHG emissions in RP and SP of each application chain.

According the GHG balances, using liquid fraction as liquid fertilizer is preferred clearly over ammonium sulphate solution and applying solid fraction as SIGM over solid fuel or fertilizer pellet. The GHG emissions of solid fuel and fertilizer pellet applications seem to follow the energy demands, while the emission ratios are lower

compared to savings of liquid fertilizer and SIGM chains. As for ammonium sulphate fertilizer, substantial emission savings deriving from nitrogen content result in avoidance of GHGs despite the high PEDs.

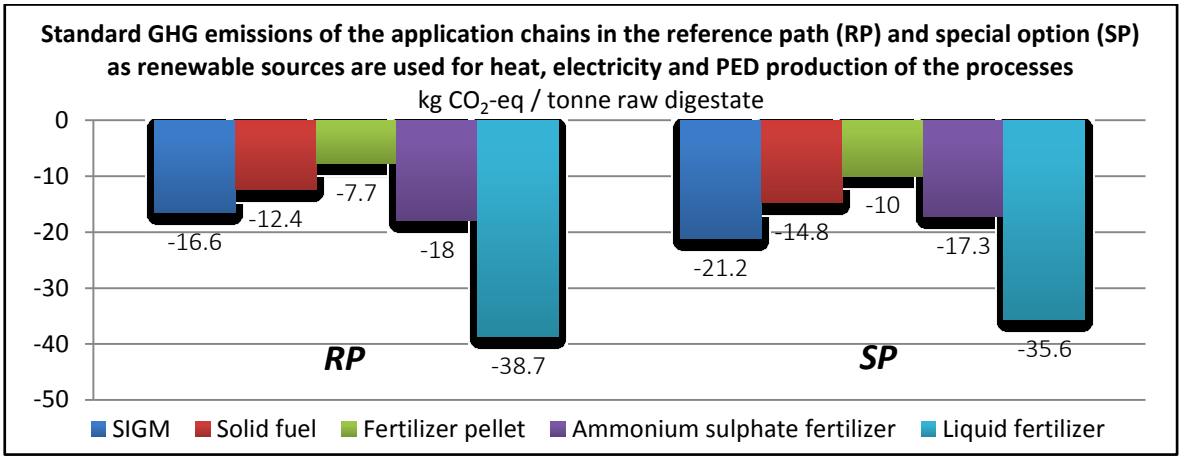

Figure 7.5 Comparison of standard GHG emissions in RP and SP of each application chain. Heat, electricity and PED for processes are produced from renewable energy sources.

7.2.1 Comparison to the study by Rehl & Müller (2011)

In their extensive study on LCA of digestate applications, Rehl & Müller include also direct emissions from e.g. storage, thermal drying and field applications, which are considered CO_2 neutral in this Thesis (Section 5.1). As a result, the chains observed in the referred report end up in GHG emission generations from less than 5 kg up to 100 kg CO_2 equivalents per tonne raw digestate. For example, when the separated solid fraction is applied to land after composting and liquid directly, emissions of ca. 10 kg CO_2 equivalents are generated. In this Thesis, the corresponding chain, energy balance of which is very similar, results in savings of more than 50 kg CO_2 equivalents. The GHG emissions are not comparable, though the ratios of different chains are more of less corresponding as e.g. the chain of fertilizer pellet applications generate the highest emissions in both studies.

7.3 Factors studied separately

In addition to the main PED and GHG calculations, few extra factors were assessed separately, including chemical hygienization, digestate origin, energy recovery and raw digestate properties. Since notable uncertainties affect most of these, more specific information should be produced to generate reliable results. For example, replacing thermal hygienization by chemical treatment could generate significant energy saving of 60 kWh per tonne raw digestate, which however is doubtful due to potential methane production increase by the thermal pretreatment. For digestate deriving entirely or partly from sewage sludge, 40 % or the phosphorous should be considered as available for plants. According to Marttinen et al. (2013), for other digestate the equivalent value should be 85 %, which generates a higher energy demand of few kilowatt hours for an application chain. Since the percentages differ considerably, high uncertainty is clear with the variable quality of the digestate.

As expected, altering the raw digestate properties affects energy and emission balances significantly since these are highly dependent on nutrient and organics contents, as discussed more specific in Section 6.3.4.1. The property alteration seems to affect the energy balance of solid fuel chain more than land application chains since the savings with the 90th percentage properties (Table 5.14) are higher than in liquid fertilizer chain, both more than 120 kWh with optimal values in RP. For GHG emissions the influence is opposite as the increase of emission savings with the 90th percentile values is notably greater in liquid fertilizer chain.

7.4 Sensitivity analysis

The reference path and special option represent a narrow sensitivity for the results. To obtain more truthful margins of error, the minimum and maximum energy demands and GHG emissions are determined for each main process and application. The ranges provided in Chapter 5 are applied to energy balances of solid-liquid separation, composting, drying, fertilizer and peat substitution, as presented in Table 7.1. Little information is available on energy demands in pelletizing and ammonia stripping of digestate: thus, standard values are utilized as minimums and optimums as maximums. Minimum PEF of heat is considered 1.00 as a result of energy recovery (Section 6.3).

Table 7.1 Minimum and maximum values used for determination of error margins for energy efficiencies and GHG emissions.

Feature	***Unit***	***PED***		***GHG***	
		MIN	*MAX*	*MIN*	*MAX*
Decanter centrifuge	kWh/t	1.8	7	-	
Screw press	kWh/t	0.24	2.1	-	
Composting	kWh/t	10	20	-	
Thermal drying	kWh/t_w[I]	720 + 8.5	1400 + 10.7	-	
Pelletizing	kWh/t	150	240	-	
Ammonia stripping	kWh/kg N	31 PED	125[II]	-	
Synthetic N-fertilizer substitution	kWh/kg N	13.4	9.1	13	4.8
Synthetic P-fertilizer substitution	kWh/kg P[III]	3.74	1.76	3.1	0.41
Peat substitution	kWh/kg SIGM	0.058	0.012	1.2	0.11
PED	PEF or SEF	1		0	0.11
Electricity	PEF or SEF	1.97		0	0.23
Heat	PEF or SEF	1[IV]	1.33	0	0.12
Diesel	PEF or SEF	1.35		0.24	0.24

I *kWh heat + kWh electricity per tonne water vaporized*
II *Per tonne matter treated*
III *PED: MIN 4.4*0.85 MAX 4.4*0.4, GHG: MIN 3.63*0.85 MAX 1.03*0.4*
IV *Energy recovery applied*

Ranges are also provided for GHG calculations in fertilizer and peat substitution. For the credits gained in applications, the largest values are applied for calculations of minimum PEDs and GHG emissions in chains, and the other way around. Minimum SEFs of PED, electricity, and heat are produced from renewable sources and, thus, are considered zero. Auxiliaries are ignored in determination of error margins due to minor influence on the values. More accurate research requires more detailed data of energy use, emissions and change of digestate properties in all of the processes and applications. In addition to the provided value ranges, uncertainty is involved in the numerous assumptions made due to lack of available data and to decrease complexity of the calculations. The results would be altered by factors and procedures, such as:

- Decreasing pH to prevent ammonia loss in thermal drying
- Energy use in thermal drying is assumed directly proportional to water removal
- Ammonia stripping efficiency (Eekert, et al., 2012)
- Solid-liquid separation efficiency: in the calculations not dependent on raw digestate properties
- The 40 % and 85 % availabilities of phosphorous in digestate are harsh generalizations
- Present value for energy demand of peat production (Seppälä, et al., 2010)
- Nutrient volatilization in the storage and land application is ignored in this study
- PEFs and SEFs
- Digestate storage as the field applications are seasonal
- Transportation distance and vehicle
- Fertilizer spreading machine and method
- Volume of the digestate in transportation
- Mass of the digestate in spreading
- In reality, more auxiliaries are needed for similar chains

7.4.1 Error margins for energy efficiencies and GHG emissions

The maximum and minimum energy efficiencies in each application chain with values provided in Table 7.1 are presented as error margins in Figure 7.1 as well as PEDs in RPs after scientific sources. Decanter centrifuge is used in the margin calculations. As expected, the wide ranges of separate processes and applications result in wide error margins. Since the ranges are provided for the main processes and applications, increase of processing generally raises variance. Thus, the chains of low energy demand, SIGM and liquid fertilizer, obtain the narrowest margins of around 20 to 30 kWh per tonne raw digestate while the range in solid fuel and fertilizer pellet chains is more than 100 kWh. High differences occur also for ammonium sulphate fertilizer, as the minimum and maximum values in ammonia stripping vary distinctively.

The maximum and minimum GHG emissions in each application chain by values provided in Table 7.1 are presented as error margins in Figure 7.2 as well as PEDs in RPs after scientific sources. For emission margins, the range is determined rather by nutrient content than number of main processes. Therefore, SIGM, ammonium sulphate fertilizer and liquid fertilizer chains obtain the widest ranges of GHG

emissions up to over 70 kg CO_2 equivalents per tonne raw digestate in SIGM application. Contrary to the margins of energy efficiency, lowest variances of ca. 15 to 30 kg CO_2 equivalents occur in solid fuel and fertilizer pellet chains. Despite the wide PED and GHG margins, the ratios of chains remain rather similar due to common variables.

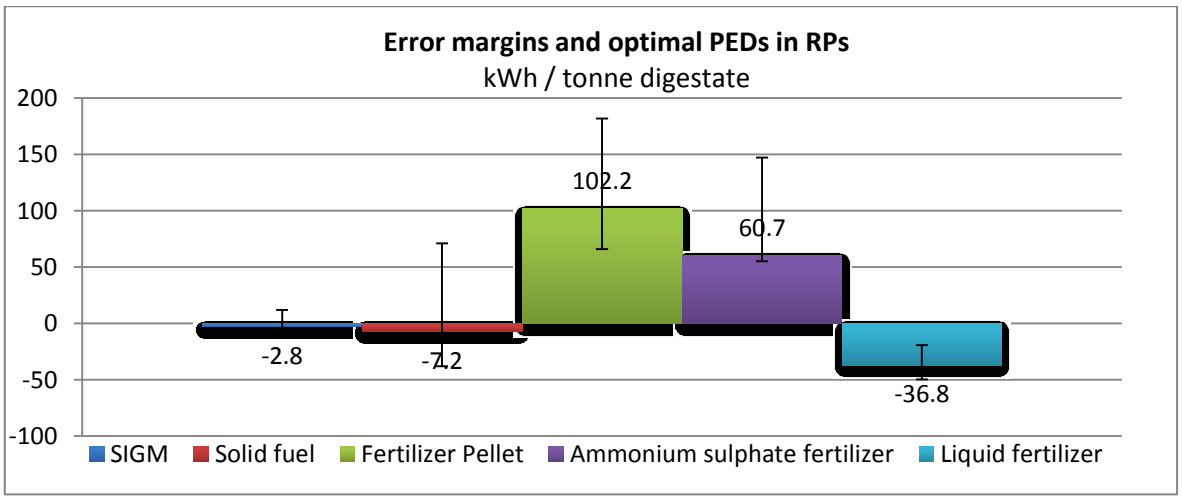

Figure 7.1 The error margins by minimum and maximum PEDs of Table 7.1 and optimal PED values in RPs of application chains.

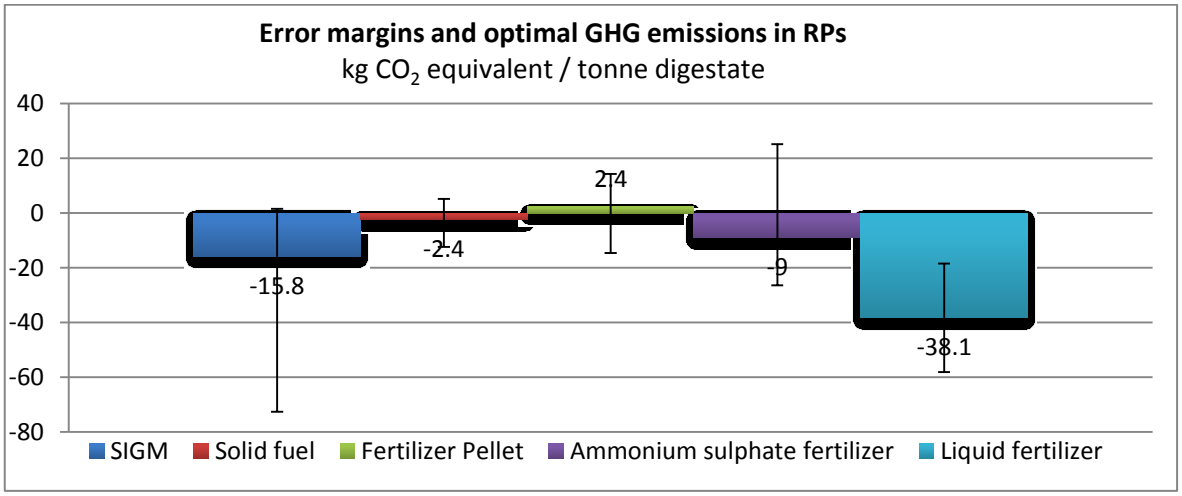

Figure 7.2 The error margins by minimum and maximum GHG emissions of Table 7.1 and optimal emissions in RPs of application chains.

8 DISCUSSION

According to the results, the most favorable procedure in terms of both energy efficiency and GHG emissions would be separation of raw digestate by screw press, which is followed by solid fraction application as soil improver-growing media (SIGM) and liquid fraction directly as fertilizer. This could generate a primary energy saving of more than 40 kWh and a GHG saving of more than 55 kg CO_2 equivalents per tonne raw digestate. Instead of SIGM, applying the solid fraction as solid fuel is more energy efficient when decanter centrifuge is used for the separation in optimal conditions. According to the gas yield table by SEAI (2010), one tonne cattle dung, chicken litter, MSW and sewage sludge generate 270 - 740 kWh of biogas. Therefore, the PED saving could account for ca. 5 – 15 % of energy content of produced biogas (the decrease of mass in AD is considered minor).

Thermal drying (90 – 225 kWh per tonne raw digestate) and ammonia stripping (65 – 145 kWh) were found the most primary energy demanding processes while the greatest energy credits are generated by substitution of synthetic N-fertilizer production (15 – 48 kWh) and energy content of solid fuel (114 – 135 kWh). Energy demands of phosphorous based spreading, 3 to 8 kWh, and transportation of liquid fertilizer over 20 km, 4 kWh, are the noteworthy auxiliaries. The N-fertilizer replacement (12 – 39 kg CO_2-eq) stands out also in GHG benefit, as e.g. the emissions of high energy demand in ammonium sulphate fertilizer chain are overrode by the nitrogen content. Energy demands generate minor emissions, as observed in the optimal PEDs of Figure 7.1 and the correspondent GHG emissions of Figure 7.3.

Generally, the simplest digestate processing results in the highest energy and emission savings while increase in number of processes worsens the balances. Exceptions are produced by the digestate properties as noted in GHG emissions of ammonium sulphate fertilizer and use of decanter centrifuge for solid fuel production: due to decreased amount of water for thermal drying, the solid fuel chain tops the energy savings of SIGM with optimal processing values. This is also observed in the alteration of raw digestate properties, in Section 6.3.4.1. Additionally, the increased processing causes greater differences between optimum and standard values for the chains of solid fuel (fertilizer pellet) and ammonium sulphate fertilizer. Especially the optimal and standard energy demand values of ammonia stripping differ substantially as few sources regarding the process seem to be available.

In fact, significant uncertainties are involved in most of the processes and applications due to lack of specific energy and GHG data: this is visible in the broad error margins discussed in previous section. Particularly the standard values should be considered doubtful as they are often chosen as averages or median values of wide ranges. On the other hand, the ratios of applications remain relatively similar in each case, and the margins would, as obvious, be directly constricted by more specific starting values. Those could be applied easily to the developed excel-tool. However, at the same time, variances of several extra factors, which could stretch the margins further and are listed in Section 7.4, are neglected by simplifications. Compared to the LCA study by Rehl & Müller (2011), the energy demands are surprisingly similar while the difference in GHG emissions derives mainly from ignorance of direct GHG emissions in this study (Section 5.1).

Of the separately studied factors, alteration of digestate properties generates the most important results. The digestate properties have remarkable effects on the chain specific energy and GHG emission values as observed in Section 6.3.4.1. The 90th percentile values of raw digestate increase the primary energy saving of solid fuel chain over the liquid fertilization chain, up to 130 kWh per tonne raw digestate, with optimal values in RP. The combination of liquid fertilizer and solid fuel application could produce a primary energy credit of as high as 250 kWh. For the GHG emissions, the influence is stronger on the land applications, up to 110 kWh in optimum of liquid fertilizer chain in RP. Rest of the separately examined factors, such as chemical hygienization and digestate origin, are considered notably doubtful and, thus, the results are only approximate.

9 CONCLUSIONS

Due to the uncertainties, the main object of this Thesis, provision of energy and emission information for further feasibility studies, is not fulfilled perfectly. The results offer doubtful information based on plenty of assumptions while, on the other hand, the calculation principles and excel-tool would generate more reliable results in the case of more specific starting values. Therefore, the secondary target of developing a convenient excel-tool is reached.

Based on the results, appropriate digestate treatment could generate noteworthy energy and GHG benefit while, on the contrary, a significant share of energy content of biogas could be consumed for production of fertilizer pellet or ammonium sulphate fertilizer. However, the energy efficiency and GHG emissions determine only a partial usability of the applications. The energy efficiency of ammonium sulphate chain is more dependent on the mass of nitrogen recovered, as evaluated by the value provided in the scientific source, than the nitrogen fertilizer substitution. Thus, the increased nitrogen recovery results in higher energy demand while the benefit gained by the handling of concentrated product is minor. Similar advantage could be achieved by the higher LHV of solid fuel after screw press use, although the increased energy demand is generated. In both cases, the grown standardization value, which is often considered essential for such a low value product, could override the higher energy consumption and GHG emissions.

Regardless, the options for standardization of digestate products are currently limited due to novelty and variable qualities of the matter. Also worth mentioning, in this study digestate was observed as individual matter while mixing it with other materials, e.g. supplementary nutrients, could improve its applicability significantly. To benefit further feasibility studies, more extensive and specific data acquisition of digestate processing would be essential as well as developing credibility of digestate products by standardization and end-of-waste criteria.

10 BIBLIOGRAPHY

151/2013, 2013. *Government Decree on Waste Incineration,* Helsinki: Finlex. In Finnish. Accessed 18.2.2014: http://www.finlex.fi/fi/laki/alkup/2006/20060539

179/2012, 2012. *Government Decree on Waste,* Helsinki: Finlex. In Finnish. Accessed 18.2.2014: http://www.finlex.fi/data/sdliite/liite/6094.pdf

2000/76/EC, 2000. *Directive 2000/76/EC of the European Parliament and of the Council on the incineration of waste,* Luxembourg: Publications office of the EU. Accessed 28.2.2014: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2000:332:0091:0111:EN:PDF

2008/98/EC, 2008. *Directive 2008/98/EC of the European Parliament and of the council on waste and repealing certain Directives,* Luxembourg: Publication office of the EU. Accessed 26.2.2014: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:312:0003:0030:EN:PDF

2010/75/EU, 2010. *Directive 2010/75/EU of the European Parliament and of the Council on industrial emissions (integrated pollution prevention and control).* Luxembourg: Publications Office of the European Union.

24/11 Appendices I-IV, 2011. *Decree of the Ministry of Agriculture and Forestry on Fertiliser Products,* Helsinki: Ministry of Agriculture and Forestry. Accessed 27.2.2014: http://www.mmm.fi/attachments/elo/newfolder/lannoiteaineet/61fAl8BFZ/MMMMa_24_11_lannoitevalmisteista_FI.PDF

331/2013, 2013. *Government Decree on Landfills,* Helsinki: Finlex. In Finnish. Accessed 28.2.2014: http://www.finlex.fi/fi/laki/alkup/2013/20130331

539/2006, 2006. *539/2006 The Act on Fertiliser Products,* Helsinki: Ministry of Agriculture and Forestry. In Finnish. Accessed 18.2.2014: http://www.finlex.fi/fi/laki/alkup/2006/20060539

86/278/EEC, 1986. *Council directive on the protection of environment, and in particular of the soil, when sewage sludge is used in agriculture,* Brussels: Official Journal of the European Communities.

91/676/EEC, 1991. *Council directive concerning the protection of waters against pollution caused by nitrates from agricultural sources,* Brussels: Official Journal of the European Communities.

Aiken, R. G. et al., 1983. *Analysis of Energy Inputs for Peat and Peatland Biomass Development,* Minnesota: University of Minnesota.

Al Seadi, T., Drosg, B. & Fuchs, W., 2013b. Biogas digestate quality and utilization. A. Wellinger, J. Murphy & D. Baxter, ed. *The biogas handbook: Science, production and applications.* Cambridge: Woodhead Publishing Limited, pp. 267 - 301.

Al Seadi, T. & Lukehurst, C., 2012. *Quality management of digestate from biogas plant used as fertiliser,* s.l.: IEA Bioenergy. Accessed 14.5.2014: http://www.iea-

biogas.net/files/daten-redaktion/download/publi-task37/digestate_quality_web_new.pdf

Al Seadi, T., Rutz, D. & Drosg, B., 2013a. Biomass resources for biogas production. A. Wellinger, J. Murphy & D. Baxter, ed. *The biogas handbook: Science, production and applications.* Cambrdige: Woodhead Publishing, pp. 19 - 51.

Al Seadi, T. et al., 2008. *Biogas Handbook.* Esbjerg, Denmark: University of Southern Denmark. Accessed 26.1.2014: http://www.lemvigbiogas.com/BiogasHandbook.pdf

Alakangas, E., 2000. *Suomessa käytettävien polttoaineiden ominaisuuksia. VTT Tiedotteita 2045.,* Espoo: VTT. ISBN 951-38-5740-9. In Finnish.

Alakangas, E., 2009. *Energy units and calculations of net calorific value and energy density as received,* s.l.: PHYDADES. Accessed 3.4.2014: http://www.biodat.eu/pages/FuelSpecificationCalculation.pdf

Arlabosse, P. et al., 2012. Efficient Sludge Thermal Processing: From Drying to Thermal Valorization. Tsotsas & E. e. al., ed. *Modern Drying Technology.* New Jersey: Wiley, pp. 295 - 324. ISBN 9783527631698.

ASCE, 2000. *Conveyance of Residuals from Water and Wastewater Treatment.* Reston, USA: American Society of Civil Engineers. ISBN 0-7844-0438-0.

Asplund, D., Korppi-Tommola, J. & Helynen, S., 2005. *Uusiutuvan Energian Lisäysmahdollisuudet Vuoteen 2015,* Helsinki: Kauppa- ja teollisuusministeriö. Accesses 11.2.2014: http://julkaisurekisteri.ktm.fi/ktm_jur/ktmjur.nsf/all/E5063805F1B754D5C22570190028414D/$file/34642005.pdf

AVI, 2011. *Boliden Kokkola Oy:n rikkihappotehtaan toimintaa ja jätevesien johtamista mereen koskevien päätösten lupamääräysten tarkistaminen, Kokkola,* Vaasa: Länsi- ja Sisä-Suomen aluehallintovirasto. In Finnish. Accessed 31.3.2014: http://www.avi.fi/documents/10191/56868/lssavi_paatos_42_2011_1_2011_5_19.pdf

AVI, 2013. *Haapaveden voimalaitoksen ympäristöluvan lupamääräysten tarkistaminen. Lupapäätös Nro 123/2013/1,* s.l.: Pohjois-Suomen Aluehallinto Virasto. In Finnish. Accessed 7.3.2014: http://www.avi.fi/documents/10191/56958/psavi_paatos_123_2013_1-2014-02-26.pdf/3a7c1546-d899-4d73-a28a-300af89ccee8

Bauer, A., Mayr, H., Hopfner-Sixt, K. & Amon, T., 2009. Detailed monitoring of two biogas plants and mechanical solid–liquid separation of fermentation residues. A. e. a. Pühler, ed. *Journal of Biotechnology vol. 142.* s.l.:Elsevier, pp. 56 - 63. ISSN 0168-1656.

Bennamoun, L., Arlabosse, P. & Léonard, A., 2013. Review on fundamental aspect of application of drying process to wastewater sludge. L. e. a. Kazmerski, ed. *Renewable and Sustainable Energy Reviews vol. 28.* s.l.:Elsevier, pp. 29 - 43. ISSN 1364-0321.

Berglund, M. & Börjesson, P., 2006. Assessment of energy performance in the life-cycle of biogas production. *Biomass and bioenergy 30.* Lund: Lund University, pp. 254 - 266.

Blumenthal, K., 2011. *Generation and treatment of municipal waste.,* s.l.: Eurostat. Accessed 14.2.2014: http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-SF-11-031/EN/KS-SF-11-031-EN.PDF

Boldrin, A., Andersen, J. K., Møller, J. & Christensen, T. H., 2009. Composting and compost utilization: accounting of greenhouse gases and global warming contributions. *Waste Management & Research vol. 27.* s.l.:Sage, pp. 800 - 812. ISSN 0734–242X.

Boundy, B., Diegel, S. W., Wright, L. & Davis, S. C., 2011. *Biomass Energy Data Book: Edition 4.* Tennessee: Oak Ridge National Library for U.S. Department of Energy.

Braun, R. & Wellinger, A., 2003. *Potential of Co-digestion. Task 37 - Energy from Biogas and Landfill Gas.,* Tulln: IEA Bioenergy.

Bröckl, M., Pesola, A. & Vanhanen, J., 2010. *Primäärienergia ja kaukolämmön kilpailukyky,* Helsinki, Finland: Gaia Consulting Oy. In Finnish. Accessed 22.4.2014: http://energia.fi/sites/default/files/primaarienergia_ja_kaukolammon_kilpailukyky_gaia.pdf

Clements, L. J., Salter, A. M., Banks, C. J. & Poppy, G. M., 2012. The usability of digestate in organic farming. *Water Science & Technology vol. 66.* s.l.:IWA Publishing, pp. 1864 - 1870. ISSN 0273-1223.

Crolla, A., Kinsley, C. & Pattey, E., 2013. Land applications of digestate. A. e. a. Wellinger, ed. *The biogas handbook.* s.l.:Woodhead Publishing, pp. 302 - 325.

DANETV, 2010. *ETV Vertification statement: GEA Westfalia separator UCA 501-00-02,* s.l.: The Danish Center for Vertification of Climate and Environmental Technologies. Accessed 11.4.2014: http://www.etv-danmark.dk/filer/energi/GEA_Post_Treatment_Verification_Statement.pdf

Debowski, M., Zielinski, M., Grala, A. & Dudek, M., 2013. Algae biomass as an alternative substrate in biogas production. *Renewable and Sustainable Energy Reviews 27.* Olsztyn, Poland: University of Warmia and Olsztyn, pp. 596 - 604.

Deublein, D. & Steinhauser, A., 2011. *Biogas from Waste and Renewable Resources: An Introduction.* 2nd edition. Weinhem: Wiley-VCH. ISBN: 978-3-527-32798-0

EC No 1069/2009, 2009. *Laying down health rules as regards animal by-products and derived products not intended for human consumption and repealing Regulation (EC) No 1774/2002 of the European Parliament and of the Council,* Luxembourg: Publications Office of the European Union.

EC No 2003/2003, 2003. *Regulation (EC) No 2003/2003 of the European Parliament and of the Council relating to ferilisers,* Luxembourg: Publications office of the EU. Accessed 27.2.2014: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:304:0001:0194:EN:PDF

EC No 834/2007, 2007. *Council regulation on organic production and labelling of organic products and repealing Regulation (EEC) No 2092/91.,* Luxembourg: Publications office of the EU. Accessed 27.2.2014: http://eur-

lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:189:0001:0023:EN:PDF

EC No 889/2008, 2008. *Comission regulation (EC) No 889/2008 on laying down detailed rules for the implementation of Council Regulation (EC) No 834/2007,* Luxembourg: Publications Office of the EU. Accessed 27.2.2014: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:250:0001:0084:EN:PDF

EC, 2006a. *Reference Document on Best Available Techniques for the Waste Treatments Industries,* s.l.: European Comission. Accessed 3.3.2014: http://eippcb.jrc.ec.europa.eu/reference/BREF/wt_bref_0806.pdf

EC, 2006b. *Reference Document on the Best Available Techniques for Waste Incineration,* Luxembourg: Publications office of the EU. Accessed 28.2.2014: http://eippcb.jrc.ec.europa.eu/reference/BREF/wi_bref_0806.pdf

EC, 2010b. *Communication from the comission to the Council and the European Parliament on future steps in bio-waste management in the European Union. COM(2010)235 final.,* Luxembourg: Publications office of the EU. Accessed 26.2.2014: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2010:0235:FIN:EN:PDF

Eekert, M. v. et al., 2012. *Explorative research on innovative nitrogen recovery. Report 51.,* Amersfoort: Stowa. ISBN 978.90.5773.585.1.

Ek, A. E. W. et al., 2011. *Slaughterhouse waste co-generation - Experiences from 15 years of full-scale operation.* Linköping, Swedish Biogas International Korea Co.

EPA, 2012. *Technology Market Summit. Case Study Primer for Participant Discussion: Biodigesters and Biogas.* Washington, U.S. Environmental Protection Agency.

EU No 142/2011, 2011. *Regulations on Implementing Regulation (EC) No 1069/2009 of the European Parliament and of the Council,* Luxembourg: Publications office of the EU. Accessed 26.2.2014: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:054:0001:0254:EN:PDF

European Comission, 2006. *An EU Strategy for Biofuels,* Brussels: EU. Accessed 13.3.2014: http://ec.europa.eu/energy/res/biomass_action_plan/doc/2006_02_08_comm_eu_strategy_en.pdf

Evans, T. D., 2009. *Using composted biosolids as a peat replacement,* Surrey: Tim Evans Environment. Accessed 13.2.2014: http://www.timevansenvironment.com/2009%20Using%20composted%20biosolids%20as%20peat%20replacement%20-%20Evans.pdf

Evira, 2013a. *Orgaanisia lannoitevalmisteita valmistavat hyväksytyt laitokset Suomessa,* s.l.: Helsinki: Evira. In Finnish. Accessed 17.2.2014: http://www.evira.fi/files/attachments/fi/kasvit/lannoitevalmisteet/raportit/hyvaksytyt_laitokset_lannvalm.pdf

Evira, 2013b. *Kansallinen lannoitevalmisteiden tyyppinimiluettelo (eng. National type designation list of fertiliser products),* Helsinki: Evira. Accessed 27.2.2014:

http://www.evira.fi/files/attachments/fi/kasvit/lannoitevalmisteet/raportit/kansallinen_lannoitevalmisteiden_tyyppinimiluettelo_id316528.pdf

Fachverband Biogas, et al., 2013. *Digestate and REACH - Position paper,* Brussels: European Biogas Association. Accessed 3.3.2014: http://european-biogas.eu/wp-content/uploads/files/2013/11/2013-11-28-Position-paper-digestate-and-REACH-EN-final.pdf

FNR, 2009. *Biogas - an introduction.* Gülzow: Fachagentur Nachwachsende Rohstoffe e.V. (FNR). Accessed 1.4.2014: http://www.bioenergyfarm.eu/media/default.aspx/emma/org/10727564/2009_FNR_Biogas_an_introduction.pdf

Ford, M. & Fleming, R., 2002. *Mechanical Solid-Liquid Separation of Livestock Manure. Literature Review,* Ridgetown: University of Guelph. Accessed 25.3.2014: http://mie.esab.upc.es/ms/informacio/residus_ramaders/Separator%20manure.pdf

Frankenhaeuser, M., 2011. *European standardization of Solid Recovered Fuels.Workshop: Processing routes for Solid Recovered Fuels.,* Dublin: CEN. Accessed 26.3.2014: http://www.ieabcc.nl/workshops/task32_Dublin_SRF/05%20Frankenhauser.pdf

Frischmann, P., 2012. *Enhancement and treatment of digestates from anaerobic digestion. Desk top study on digestate enhancement and treatment.,* s.l.: WRAP.

Fuchs, W. & Drosg, B., 2013. Assessment of the state of the art of technologies for the processing of digestate residue from anaerobic digesters. *Water Science & Technology.* Tulln: IWA Publishing, pp. 1984 - 1993.

Gasum Oy, 2012. *Gasum Oy:n maakaasutoimitusten yleiset ehdot.* Accessed 13.3.2014: http://www.energiavirasto.fi/documents/10179/0/VAHVISTETTU_M2010_Maakaasutoimitusten_Yleiset_Ehdot_2012.pdf

GEA, 2014. *Specific Energy Consumption UCD 205. GEA Westfalia Separator,* s.l.: s.n. Personal communication on 24.3.2014 with Janne Koistinen, GEA.

GN Centrifuge, 2013. *Decanter Centrifuge Factors - Screw Conveyor.* Accessed 4.4.2014: http://www.gncentrifuge.com/Blogs/decanter-centrifuge-factors-screw-conveyor.html

Gujer, W. & Zender, A., 1983. Conversion Processes in Anaerobic Digestion. Teoksessa: *Wat.Sci.Tech. Vol. 15.* Copenhagen: Pergamon Press, pp. 127 - 167. Accessed 14.3.2014: http://www.iwaponline.com/wst/01508/0127/wst015080127.pdf

Guštin, S. & Marinšek-Logar, R., 2011. Effect of pH, temperature and air flow rate on the continuous ammonia stripping of the anaerobic digestion effluent. J. e. a. Perkins, ed. *Process Safety and Environmental Protection vol. 89.* s.l.:Elsevier, pp. 61 - 66. ISSN 09575820

Hahn, H. & Hoffstede, U., 2010. *Final assesment report of residual materials,* Lille: Biogasmax. Accessed 13.5.2014: http://www.transport-research.info/Upload/Documents/201206/20120601_135230_63292_d2_13_biogasmax_iwes_vfinal_nov2010__096562800_1109_10022011.pdf

Havukainen, J., Horttanainen, M. & Linnanen, L., 2012. *Feasibility of ASH DEC- process in treating sewage sludge and manure ash in Finland,* Lappeenranta, Finland: Lappeenranta University of Technology. ISBN 978-952-265-329-1. Accessed 25.2.2014: http://www.doria.fi/bitstream/handle/10024/90919/isbn9789252653307.pdf

Havukainen, J. et al., 2013. Evalution of methods for estimating energy performance of biogas production. Teoksessa: *Renewable Energy 66.* Lappeenranta: Lappeenranta University of Technology, pp. 232 - 240.

Hjorth, M., Christensen, K., Christensen, M. & Sommer, S., 2010. Solid–liquid separation of animal slurry in theory and practice. A review. E. e. a. Lichfouse, ed. *Agronomy for sustainable development vol. 30.* s.l.:s.n., pp. 153 - 180. ISSN 1773-0155.

Hokkanen, M., 2009. *BT Biopresser-25:n soveltuvuus eräiden korsibiomassojen pelletöintiin. BDC Publications 43.,* Jyväskylä: Jyväskylän Ammattikorkeakoulu. In Finnish. Accessed 12.3.2014: https://publications.theseus.fi/bitstream/handle/10024/20519/Matti_43.pdf

Hupponen, M., Luoranen, M. & Horttanainen, M., 2012. *Mädätysjäännöksen rakeistus, terminen kuivaus ja energiahyötykäyttö. LUT energia. Tutkimusraportti 24.,* Lappeenranta, Finland: Lappeenrannan University of Technology. ISBN 978-952-265-286-7. In Finnish.

Huttunen, M. J. & Kuittinen, V., 2013. *Suomen biokaasulaitosrekisteri n:o 16. Tiedot vuodelta 2012.,* Joensuu: The University of Eastern Finland. In Finnish. Accessed 22.3.2014. http://epublications.uef.fi/pub/urn_isbn_978-952-61-1237-4/urn_isbn_978-952-61-1237-4.pdf

Häkkinen, E. & Merilehto, K., 2012. *Valtakunnallisen jätesuunnitelman seuranta. Ympäristöministeriön raportteja 3 / 2012,* Helsinki: Ympäristöministeriö. ISBN 978-952-11-3970-3.

IPCC, 2013. *Climate Change 2013. The Physical Science Basis. Summary for Policy Makers.,* Bern: IPCC, Switzerland. Accessed 21.1.2014: https://www.ipcc.ch/report/ar5/wg1/docs/WGIAR5_SPM_brochure_en.pdf

IPCC, 2007. *Climate Change 2007: Working Group I: The Physical Science Basis,* New York: Cambridge University Press. Accessed 28.1.2014: http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm

ISWA Working Group, 2013. *FACT SHEET: Requirements for the Treatment and Application of Digestate and Sewage Sludge (Biosolids) - Cases of several countries,* s.l.: International Solid Waste Association.

Jansen, J. l. C., 2011. Anaerobic Digestion: Technology. T. H. Christensen., ed. *Solid Waste Technology and Management.* Lund: Blackwell Publishing Ltd., pp. 601 - 617. ISBN: 978-1-405-17517-3.

John, E. & Singh, K., 2011. Production and Properties of Fuels from Domestic and Industrial Waste. *Biofuels Handbook.* Cambridge: RSC Publishing, pp. 333 - 373.

Johnson, M. C., Palou-Rivera, I. & Frank, E. D., 2013. Energy consumption during the manufacture of nutrients for algae cultivation. *Algal Research vol. 2.* s.l.:Elsevier, pp. 426 - 436. ISSN 2211-9264.

Kaakkois-Suomen Ympäristökeskus, 2005. *Ympäristölupapäätös Dnro KAS-2004-Y-312-111. Päätös ympäristönsuojelulain 35 §:n mukaisesta ympäristölupahakemuksesta.,* Kouvola: Kaakkois-Suomen Ympäristökeskus.

Keto, M., 2010. *Energiamuotojen kerroin. Yleiset perusteet ja toteutuneen sähkön- ja lämmöntuotannon kertoimet. Raportti Ympäristöministeriölle.,* Espoo, Finland: Aalto University. In Finnish. Accessed 20.3.2014: http://www.ym.fi/download/noname/%7BA6ABCFF7-55FA-412C-A0C7-FEE5CC0A2F24%7D/30744

King, C. & Bardos, P., 2013. *Evidence for digestate use in different UK markets: an annotated bibliography,* Oxon: WRAP. Accessed 13.2.2014: http://www.localnet.abertay.ac.uk/media/Evidence%20for%20digestate%20use%20in%20different%20UK%20markets%20-%20an%20annotated%20bibliography.pdf

King, C., Bardos, P. & Nortcliff, S., 2013. *Market expectations and requirements for digestate. Final Report.,* s.l.: WRAP. Accessed 8.2.2014: http://www.wrap.org.uk/sites/files/wrap/Market%20expectations%20and%20requirements%20for%20digestate%20report.pdf

Kratzeisen, M. et al., 2010. Applicability of biogas digestate as solid fuel. J. e. a. Patrick, ed. *FUEL vol. 89.* s.l.:Elsevier, pp. 2544 - 2548. ISSN 0016-2361.

Kukko, L., 2009. *Jätevedenpuhdistuksen elinkaarikustannukset energia- ja ainetaseiden kautta,* Tampere, Finland: Tampere University of Applied Sciences. In Finnish. Accessed 9.4.2014: http://publications.theseus.fi/bitstream/handle/10024/8560/Kukko.Laura.pdf?sequence=2

Käytännön maamies, 2012. *Orgaaniset lannoitevalmisteet 2012,* Espoo: KM. In Finnish. Accessed 17.2.2014: http://kaytannonmaamiesfi.virtualserver27.hosting.fi/wp-content/uploads/2013/12/Orgaaniset-lannoitevalmisteet-2012.pdf

Lako, P., 2009. *Energy conservation potential of the nitrogen fertiliser industry,* s.l.: Energy Research Center of Netherlands. Accessed 12.5.2014: http://www.ecn.nl/docs/library/report/2009/e09011.pdf

Lampinen, A., 2009. *Uusiutuvan liikenne-energian tiekartta.* Joensuu: Pohjois-Karjalan Ammattikorkeakoulu. ISBN 978-951-604-101-1. In Finnish.

Latvala, M., 2009. *Biokaasun tuotanto suomalaisessa toimintaympäristössä,* Helsinki: Suomen Ympäristökeskus. In Finnish. Accessed 12.3.2014: https://helda.helsinki.fi/bitstream/handle/10138/37998/SY_24_2009.pdf?sequence=1

Lebuf, V. et al., 2012. *Nutrient recovery from digestates: techniques and end-products.* Venice, Fourth International Symposium on Energy from Biomass and Waste.

Lehtomäki, A., 2007. *Energy from waste – Sustainable energy production with biogas technology.* Jyväskylä, Finland: Jyväskylä Innovation Ltd. Accessed 18.3.2014:

http://www.vtt.fi/proj/ecocitychina/presentations/Energy_from_waste_Lehtomaki.pdf

Lehto, P., 2010. *Biokaasulaitoksen rejektivesien vaikutus jätevedenpuhdistamon toimintaan ja rejektiveden esikäsittelyn tarpeellisuus,* Lappeenranta: Lappeenranta University of Technology. In Finnish. Accessed 9.4.2013: http://www.kouvola.fi/material/attachments/5nm0phRsx/5qBBr7WPl/Diplomityo_lehto.docx.pdf

Lohiniva, E., Mäkinen, T. & Sipilä, K., 2001. *Lietteiden käsittely: Uudet ja käytössä olevat tekniikat. Research Notes 2081.,* Espoo: Technical Research Center of Finland (VTT). ISBN 951–38–5796–4. In Finnish.

Lukehurst, C. T., Frost, P. & Al Seadi, T., 2010. *Utilisation of digestate from biogas plants as biofertiliser,* Kent: IEA Bioenergy.

Luostarinen, S., 2013. *Biokaasuteknologiaa maatiloilla I. Biokaasulaitoksen hankinta, käyttöönotto ja operointi - käytännön kokemuksia MTT:n maatilakohtaiselta laitokselta. MTT raportti 113.,* Jokioinen: MTT. ISBN 978-952-487-481-6. In Finnish.

Luostarinen, S. et al., 2011. *Lannan ja muun eloperäisen materiaalin käsittelyteknologiat. MTT raportti 27.,* Jokioinen, Finland: MTT. ISBN 978-952-487-333-8. In Finnish.

Luste, S. & Luostarinen, S., 2010. Anaerobic co-digestion of meat-processing by-products and sewage sludge – Effect of hygienization and organic loading rate. S. e. a. Ricke, ed. *Bioresource Technology vol. 101.* s.l.:Elsevier, pp. 2657 - 2664. ISSN 0960-8524.

Marttinen, S. et al., 2013. *Biokaasulaitosten lopputuotteet lannoitevalmisteina. MTT raportti 82.,* Jokioinen: MTT Jokioinen. In Finnish. Accessed 9.4.2014: http://www.mtt.fi/mttraportti/pdf/mttraportti82.pdf

Matuana, L. & Gould, M. C., 2006. *Promoting the Use of Digestate from Anaerobic Digesters in Composite Materials. Final report.,* Michigan: Michigan Biomass Energy Program. Accessed 24.2.2014: https://www.msu.edu/~matuana/images/CompositesProjectFinalReport1.pdf

Maunuksela, L., Herranen, M. & Torniainen, M., 2012. Quality Assessment of Biogas Plant End Products by Plant Bioassays. S. Bady, ed. *International Journal of Environmental Science and Development vol. 3.* Singapore: IACSIT Press, pp. 305 - 310. ISSN 2010-0264.

Maurer, C. & Müller, J., 2012. Ammonia (NH3) emissions during drying of untreated and dewatered biogas digestate in a hybrid waste-heat/solar dryer. T. e. a. Bley, ed. *Engineering in Life Sciences vol. 12.* s.l.:Wiley, pp. 321 - 326. ISSN 1618-2863

Mavi, 2009. *Opas ympäristötuen ehtojen mukaiseen lannoitukseen 2007–2013,* Helsinki: Maaseutuvirasto. In Finnish. Accessed 11.4.2014: http://www.mavi.fi/fi/oppaat-ja-lomakkeet/viljelija/Documents/Opas%20ymp%C3%A4rist%C3%B6tuen%20ehtojen%20mukaiseen%20lannoitukseen%202007-2013.pdf

Ministry of Employment and the Economy, 2011. *Laki uusiutuvilla energialähteillä tuotetun sähkön tuotantotuesta 1396/2010,* Helsinki: Finlex. Accessed 25.3.2014: http://www.edilex.fi/smur/20101396

Ministry of the Environment, 2010. *Biohajoavista jätteistä enemmän energiaa. Biojäte-energiatyöryhmän raportti. Ympäristöministeriön raportteja 3/2010.,* Helsinki: Edita Prima Oy. ISBN 978-952-11-3720-4. In Finnish.

Monnet, F., 2003. *An Introduction to Anaerobic Digestion of Organic Wastes.* Accessed 16.3.2014: http://www.biogasmax.co.uk/media/introanaerobicdigestion__073323000_1011_24042007.pdf

Motiva, 2010. *Energiatehokkuussopimukset: Polttoaineiden lämpöarvot, hyötysuhteet ja hiilidioksidin ominaispäästökertoimet sekä energian hinnat,* Helsinki, Finland: Finnish Ministry of Employment and the Economy.

MTT, 2012. *LeviLogi-hanke: Esimerkkituotteen kuvaus. Orgaaniset lannoitevalmisteet lähialueiden tilojen käyttöön.,* s.l.: LeviLogi. In Finnish. Accessed 7.3.2014: https://portal.mtt.fi/portal/page/portal/mtt/hankkeet/levilogi/esimerkkituotteet/Maanparannusrae%20LE%20Juliste.pdf

Mudhoo, A., 2012. *Biogas production. Pretreatment Methods in Anaerobic Digestion.* Massachusetts: Scrivener Publishing. ISBN: 978-1-118-06285-2.

Myllymaa, T. et al., 2008a. *Jätteiden kierrätyksen ja polton käsittelyketjujen ympäristökuormitus ja -kustannukset. Inventaarioraportti.,* Helsinki: Suomen Ympäristökeskus. In Finnish.

Myllymaa, T. et al, 2008b. *Jätteiden kierrätyksen ja polton ympäristövaikutukset ja kustannukset – jätehuollon vaihtoehtojen tarkastelu alueellisesta näkökulmasta,* Helsinki: Suomen Ympäristökeskus. ISBN 978-952-11-3235-3. In Finnish.

Myllymaa, T., Tohka, A., Dahlbo, H. & Tenhunen, J., 2006. *Ympäristönäkökulmat jätteen hyödyntämisessä energiana ja materiaalina. Valtakunnallinen jätesuunnitelma vuoteen 2016. Taustaselvitys Osa III. SYKE raportteja 12.,* Helsinki, Finland: Finnish Environment Institute. In Finnish. Accessed 15.4.2014: http://www.ym.fi/download/noname/%7B0D218FEA-B97A-41E5-AEDD-CF3B11E8E443%7D/30372

Mäkelä, K., 2012. *LIPASTO -emission calculation system, VTT: Delivery lorry, heavy.* Accessed 20.3.2014: http://lipasto.vtt.fi/yksikkopaastot/tavaraliikennee/tieliikennee

Møller, H., Hansen, J. & Sørensen, C., 2007. Nutrient recovery by solid-liquid separation and methane productivity of solids. *Transactions of the ASABE vol. 50.* s.l.:American Society of Agricultural and Biological Engineers, pp. 193 - 200. ISSN 0001-2351.

Møller, H., Sommer, S. & Ahring, B., 2002. Separation efficiency and particle size distribution in relation to manure type and storage conditions. *Bioresource Technology vol. 85.* s.l.:Elsevier, pp. 189 - 196. ISSN 0960-8524.

Møller, J., Boldrin, A. & Christensen, T. H., 2009. *Anearobic digestion and digestate use: accounting of greenhouse gases and global warming contribution,* Kongens Lyngby: Technical University of Denmark.

Møller, J., Christensen, T. & Jansen, J., 2011. Anaerobic Digestion: Mass Balances and Products. T. Christensen, ed. *Solid Waste Technology & Management.* s.l.:Blackwell Publishing Ltd, pp. 618-627. ISBN: 978-1-405-17517-3.

NRCS, 2009. Chapter 10: Agricultural Waste Management System Component Deisgn. *Agricultural Waste Management Field Handbook.* s.l.:U.S. Department of Agriculture.

Paavola, T., 2013. *Mädätyksen lopputuotteet ja niiden käyttö.* Jokioinen, Finland, Biovakka Oy. In Finnish. Accessed 13.2.2014: http://files.kotisivukone.com/biolaitosyhdistys.palvelee.fi/paavola.pdf

Paavola, T., Luostarinen, S., Kaparaju, P. & Rintala, J., 2009. Increasing Overall Energy Impact of Biogas Concepts through Processing Digestate to Valuable Products. M. Savolainen, ed. *Bioenergy 2009. Book of proceedings part II. 4th International Bioenergy Conference..* Jyväskylä: FINBIO, pp. 985 - 989. ISBN 978-952-5135-44-2.

Paavola, T. & Rintala, J., 2006. *Effect of hygienisation (1 hour at 70 C) on methane production of manure, biowaste and sewage sludge.* s.l., IWWG.

Panek-Gondek, K., 2012. *IED and BREF Revision.* Accessed 25.4.2014: http://www.cepi.org/system/files/public/epw-presentations/2012/BREFseminar/Paper%20week.pdf

Partanen, E., 2010. *Mädätysjäännöksen tuotteistamismahdollisuudet Kymenlaaksossa,* Lappeenranta: Lappeenranta University of Technology. In Finnish. Accessed 3.2.2014: http://www.doria.fi/bitstream/handle/10024/66351/EsaPartanen_madatysjaannos_diplomityo2010_LutPub.pdf?sequence=1

Pelkonen, R., 2013. *Maatalouden biokaasulaitoksen ympäristölupa. Opas toiminnanharjoittajille sekä lupa- ja valvontaviranomaisille. Suomen Ympäristökeskuksen raportteja 33/2013.,* Helsinki: Finnish Environment Institute. ISBN 978-952-11-4232-1. In Finnish.

Persson, M., Jönsson, O. & Wellinger, A., 2006. *Biogas Upgrading to Vehicle Standards and Grid Injection.* Malmö, IEA Bioenergy.

Piccinini, S., Moscatelli, G. & Fabbri, C., 2013. *Nitrogen recovery from digestate with ammonia stripping: results of 27 tests,* Bruges: CRPA - Reggio E. Accessed 4.4.2014: http://www.crpa.it/media/documents/crpa_www/Convegni/20131206_manureResource_BELGIO/Piccinini_Ammonia_Stripping.pdf

Pohjois-Suomen Ympäristölupavirasto, 2006. *Ympäristölupapäätös nro 97/06/2. Raahen kalkinpolttamon ympäristölupa. Nordkalk Oyj Abp.,* Oulu, Finland: s.n. In Finnish.

Pöyry Environment Oy, 2007. *Lietteenkäsittelyn nykytila Suomessa ja käsittelymenetelmien kilpailukyky -selvitys,* s.l.: Sitra. ISBN 978-951-563-597-6. In Finnish.

Recchia, L. et al., 2011. *Multicriteria Analysis and LCA Techniques With Applications to Agro-Engineering Problems.* London: Springer. ISSN 1865-3529.

Rehl, T. & Müller, J., 2011. Life cycle assessment of biogas digestate processing technologies. E. e. a. Worrell, ed. *Resources, Conservation and Recycling vol. 56.* s.l.:Elsevier, pp. 92 - 104. ISSN 0921-3449.

Restrepo, A. P. et al., 2013. Substitution of Peat in Horticultural Seedlings: Suitability of Digestate-Derived Compost from Cattle Manure and Maize Silage Codigestion. *Communications in Soil Science and Plant Analysis vol. 44.* s.l.:Taylor & Francis Group, pp. 668 - 677. ISSN 0010-3624.

Rigby, H. & Smith, S. R., 2011. *New Markets for Digestate from Anaerobic Digestion. Desktop study on new markets.,* London: WRAP. Accessed 15.3.2014: http://www.wrap.org.uk/sites/files/wrap/New_Markets_for_AD_WRAP_format_Final_v2.c6779ccd.11341.pdf

Sandars, D. et al., 2003. Environmental Benefits of Livestock Manure Management Practices and Technology by Life Cycle Assessment. *Biosystems Engineering vol. 84.* s.l.:Elsevier, pp. 267 - 281. ISSN 1537-5110.

Sauramo, J., 2009. *Mass and energy balance of ammonia recovery plant,* Pori, Finland: Satakunta University of Applied Sciences. Accessed 28.4.2014: https://www.theseus.fi/bitstream/handle/10024/4464/Sauramo_Jenni.pdf?sequence=1

Saveyn, H. & Eder, P., 2014. *End-of-waste criteria for biodegradable waste subjected to biological treatment (compost & digestate): Technical proposals. JRC Scientific and Policy Reports.,* Luxembourg: Publications Office of the European Union. ISBN 978-92-79-35062-7.

Scholwin, F. & Nelles, M., 2013. Energy flows in biogas plants: analysis and implications for plant design. A. e. a. Wellinger, ed. *The biogas handbook: Sciene, production and applications.* Cambridge: Woodhead Publishing Limited, pp. 212 - 227. ISBN 978-0-85709-498-8

SEAI, 2010. *Gas Yields Table,* s.l.: Sustainable Energy Authority of Ireland. Accessed 22.5.2014: http://www.seai.ie/Renewables/Bioenergy/Bioenergy_Technologies/Anaerobic_Digestion/The_Process_and_Techniques_of_Anaerobic_Digestion/Gas_Yields_Table.pdf

Seppälä, J. et al., 2010. *Climate impacts of peat fuel utilization chains – a critical review of the Finnish and Swedish life cycle assessments,* Helsinki, Finland: The Finnish Environment Institute. Accessed 14.5.2014: https://helda.helsinki.fi/bitstream/handle/10138/37984/FE_16_2010.pdf?sequence=5

Seppänen, R. et al., 2005. *Maol taulukot.* 2nd edition. Keuruu: Otava. ISBN 951-1-20607-9.

Shirani, A. & Evans, M., 2012. *Driving Innovation in AD Optimisation – Uses for Digestate,* s.l.: WRAP. Accessed 26.3.2014: http://www.wrap.org.uk/sites/files/wrap/DIAD%20I%20AWS%20Burdens%20feasibility%20report.pdf

Sinkko, T., Manninen, K. & Rasi, S., 2012. *Biokaasuketjun kasvihuonekaasupäästöt,* Helsinki, Finland: Suomen maataloustieteellinen seura. In Finnish. Accessed 22.5.2014: http://www.smts.fi/Maa-%20ja%20puutarhatalouden/Sinkko_Biokaasuketjun.pdf

Spaey, D., Traon, D. & Joas, R., 2012. *Study on options to fully harmonise the EU legislation on fertilising materials including technical feasibility, environmental, economic and social impacts,* Brussels: The European Comission. Accessed 11.2.2014: http://ec.europa.eu/enterprise/sectors/chemicals/files/fertilizers/final_report__23jan2012_en.pdf

Spelter, H., Winandy, J. & Zauche, T., 2008. Anaerobically digested bovine biofiber as a source of fiber for particleboard manufacturing: an economic analysis. *BioResources vol. 3 .* North Carolina: NC State University, pp. 1256 - 1266.

Stamatelatou, K., Antonopoulou, G. & Lyberatos, G., 2011. Production of biogas via anaerobic digestion. *Handbook of Biofuel Production.* s.l.:Woodhead Publishing. ISBN: 978-1-84569-679-5.

Statistics Finland, 2009. *Greenhouse Gas Emissions in Finland 1990 - 2007. National Inventory Report under the UNFCCC and the Kyoto Protocol.,* Helsinki, Finland: Statistics Finland. Accessed 13.5.2014: http://www.stat.fi/tup/khkinv/fi_nir_030409.pdf

Statistics Finland, 2014. *Polttoaineluokitus 2014,* Helsinki, Finland: Official statistics of Finland. In Finnish. Accessed 22.4.2014: http://www.stat.fi/tup/khkinv/khkaasut_polttoaineluokitus_2014.xls

Suvilampi, K., 2013. *Ravinteiden kierrätyksen edistäminen ja Saaristomeren tilan parantaminen.* Turku, Biotehdas Oy. In Finnish. Accessed 13.2.2014: http://www.biotehdas.fi/media/uploads/pdf/bioravinneporssi-raki-seminaari-09-10-2013-turku.pdf

Svoboda, I. F., 2003. *Anaerobic digestion, storage, oligolysis, lime, heat and aerobic treatment of livestock manures,* Warwickshire, Scotland: FEC Services. Accessed 31.3.2014: http://www.scotland.gov.uk/Resource/Doc/1057/0002224.pdf

Syers, K. et al., 2011. Phosphorus and Food Production. T. Goverse & S. Bech, ed. *Unep Year Book 2011.* Nairobi, Kenya: United Nations Environment Programme, pp. 35 - 45. ISBN 978-92-807-3101-9.

Tambone, F. et al., 2010. Assessing amendment and fertilizing properties of digestates from anaerobic digestion through a comparative study with digested sludge and compost. X. Cao, ed. *Chemosphere vol. 81.* s.l.:Elsevier, pp. 577 - 583. ISSN 0045-6535.

Teater, C. et al., 2011. Assessing solid digestate from anaerobic digestion as feedstock for ethanol production. A. Pandey, ed. *Bioresource Technology vol. 102.* s.l.:Elsevier, pp. 1856-1862. ISSN 0960-8524.

Teglia, C., Tremier, A. & Martel, J.-L., 2011. Characterization of Solid Digestates: Part 1, Review of Existing Indicators to Assess Solid Digestates Agricultural Use. *Waste Biomass Valor (2011) 2.* s.l.:Springer Science+Business Media, pp. 43 - 58. DOI 10.1007/s12649-010-9051-5.

Thunberg, A., 2010. *Optimizing Sludge Dewatering by Using the KemiCond Process with the Bucher Hydraulic Filter Press – Full Scale Experiences at Käppala WWTP. Residuals and Biosolids.,* Lidingö, Sweden: Käppala. Accessed 28.3.2014: http://www.kappala.se/Global/Rapporter/Processutvecklingsrapporter/Opt

imizing%20sludge%20dewatering%20by%20using%20Kemicond%20process_2010.pdf

Tontti, T., Kangas, A. & Högnäsbacka, M., 2010. *Yhdyskuntajätteen ravinteet pellolle ja viheralueelle. MTT raportti 10.,* Jokioinen, Finland: MTT. ISBN 978-952-487-290-4. In Finnish. Accessed 17.2.2014: http://jukuri.mtt.fi/bitstream/handle/10024/438211/mttraportti10.pdf?sequence=1

Uusitalo, R. et al., 2007. *Maatalous Itämeren rehevöittäjänä. Maa- ja elintarviketalous 96.,* Jokioinen: MTT. In Finnish. Accessed 4.3.2014: http://www.mtt.fi/met/pdf/met96.pdf

Wellinger, A., 1999. *Process design of agricultural digesters,* Ettenhausen: Nova Energie Gmbh. Accessed 9.2.2014: http://homepage2.nifty.com/biogas/cnt/refdoc/whrefdoc/d14prdgn.pdf

Wesnæs, M., Hamelin, L. & Wenzel, H., 2013. *Life Cycle Inventory & Assessment Report: Separation of Digested Fattening Pig Slurry for Optimal P Concentration, Denmark,* s.: Baltic Manure. Accessed 11.4.2014: http://balticmanure.eu/download/Reports/lca_report_on_seperation_web.pdf

White, P. R., Franke, M. & Hindle, P., 1995. *Integrated Solid Waste Management: A lifecycle inventory.,* New York, the USA: Aspen. ISBN 0-8342-1311-7.

Wilkie, A. C. & Mulbry, W. W., 2002. Recovery of dairy manure nutrients by benthic freshwater algae. A. e. a. Pandey, ed. *Bioresource Technology vol. 84.* s.l.:Elsevier, pp. 81 - 91. ISSN 09608524.

Williams, J. & Esteves, S., 2011. *Digestates: Characteristics, Processing and Utilisation.* Glamorgan: The Wales AD Center. Accessed 11.3.2014: http://biomethaneregions.cra.wallonie.be/img/download/TrainingTheTrainers_UK_Digestate_Characteristics_and_Processing.pdf

Vuorinen, A. et al., 2013. *Puhdistamolietteen käyttö maataloudessa,* Helsinki: Ministry of Agriculture and Forestry of Finland. In Finnish. Accessed 14.3.2014: http://www.mmm.fi/attachments/elo/newfolder/lannoiteaineet/6J0lEpdSu/Puhdistamolietteen_kaytto_maataloudessa.pdf

Wäänänen, M., 2011. *Maanparannuskompostin maatalouskäyttö.* Helsinki, HSY Vesihuolto. In Finnish. Accessed 13.2.2014: http://files.kotisivukone.com/biolaitosyhdistys.palvelee.fi/tiedostot/2011seminaari/waananen.pdf

Yue, Z. et al., 2010. A Sustainable Pathway of Cellulosic Ethanol Production Integrating Anaerobic Digestion With Biorefining. D. S. Clark, ed. *Biotechnology and Bioengineering vol. 105.* s.l.:Wiley, pp. 1031-1039. ISSN 00063592.

Zeng, T. & Pollex, A., 2012. *Overview about national conditions. Katsaus kansallisiin olosuhteisiin* s.l.: MixBioPells. In Finnish. Accessed 26.3.2013 http://www.mixbiopells.eu/fileadmin/user_upload/WP4/D4_3_Overview_about_national_conditions/D4_3_Overview_about_national_conditions_FI_VTT.pdf

APPENDICES

Appendix 1: Flow chart of digestate processing options

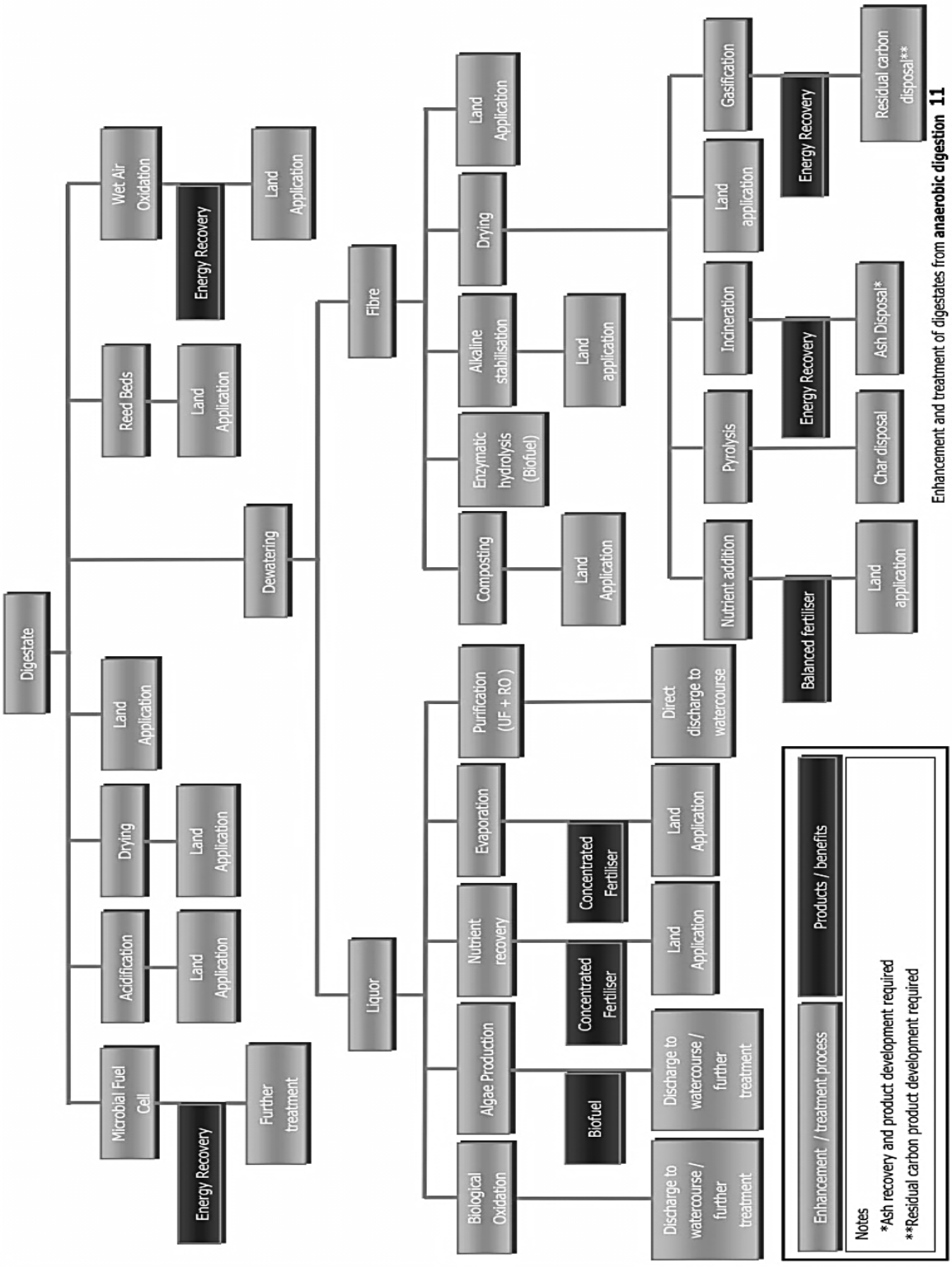

Figure A1.1 Different processing options for digestate in the chart from the report by Frischmann (2012).

Appendix 2: Classification system of solid recovered fuels

Table A2.1 Classification system of SRFs according to CEN/TS 15359 standard. Adapted from the report by Frankenhaeuser (2011).

Classification Property	**Statistical Measure**	**Unit**	**Classes**				
			1	**2**	**3**	**4**	**5**
Net calorific value **(NCV)**	Mean	MJ/kg/(ar)	**≥ 25**	**≥20**	**≥15**	**≥10**	**≥ 3**
Classification Property	**Statistical Measure**	**Unit**	**Classes**				
			1	**2**	**3**	**4**	**5**
Chlorine **(Cl)**	Mean	% (d)	**≤0,2**	**≤0,6**	**≤1,0**	**≤1,5**	**≤3**
Classification Property	**Statistical Measure**	**Unit**	**Classes**				
			1	**2**	**3**	**4**	**5**
Mercury **(Hg)**	Median	mg/MJ (ar)	**≤0,02**	**≤0,03**	**≤0,08**	**≤0,15**	**≤0,50**
	80^{th} percentile	mg/MJ (ar)	**≤0,04**	**≤0,06**	**≤0,16**	**≤0,30**	**≤1,00**

Appendix 3: Operation tab in the excel-tool

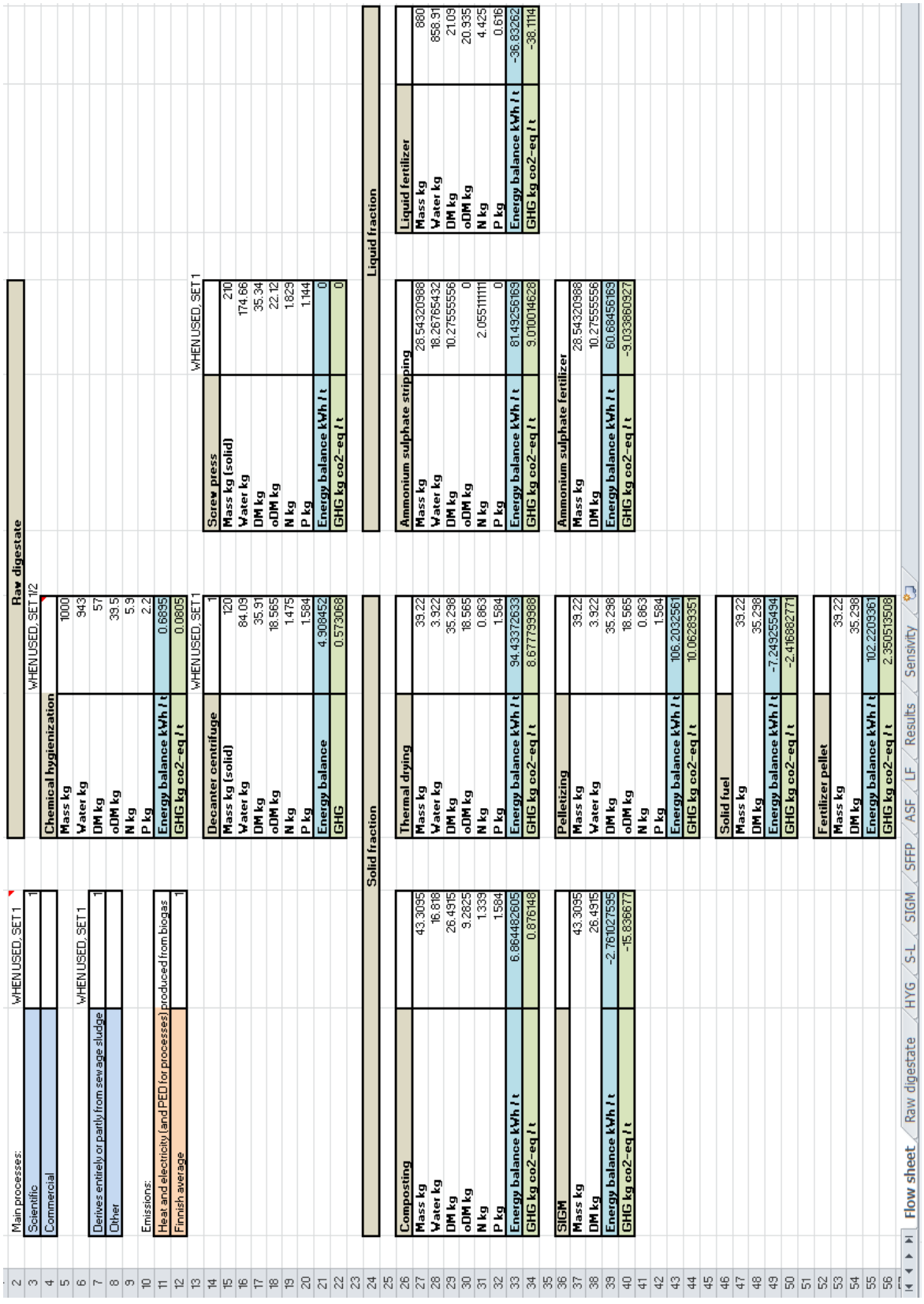

Figure A3.1 Operation tab of the developed excel-tool, which includes properties of the matter, PEDs and GHG emissions in concatenated processes and application.

Appendix 4: Figures of process specific PEDs

Process specific optimum and standard energy balances in RP and SP of each application chain are presented in Figures A4.1 – A4.16. *RP* stands for *reference path* and *SP* for special option of using *screw press* instead of decanter centrifuge. Energy use of an auxiliary process, e.g. pumping or transportation, following a specific main process (shown in Figure 5.1) is included in the energy balance of the main process. As exceptions, the pumping of raw digestate is included in the solid-liquid separation, transportation of liquid fertilizer is included in the application and spreading is always included in the application. The energy consumptions of solid-liquid separation and pumping or raw digestate are included totally in the chains, without allocation to solid and liquid fractions.

SIGM chain

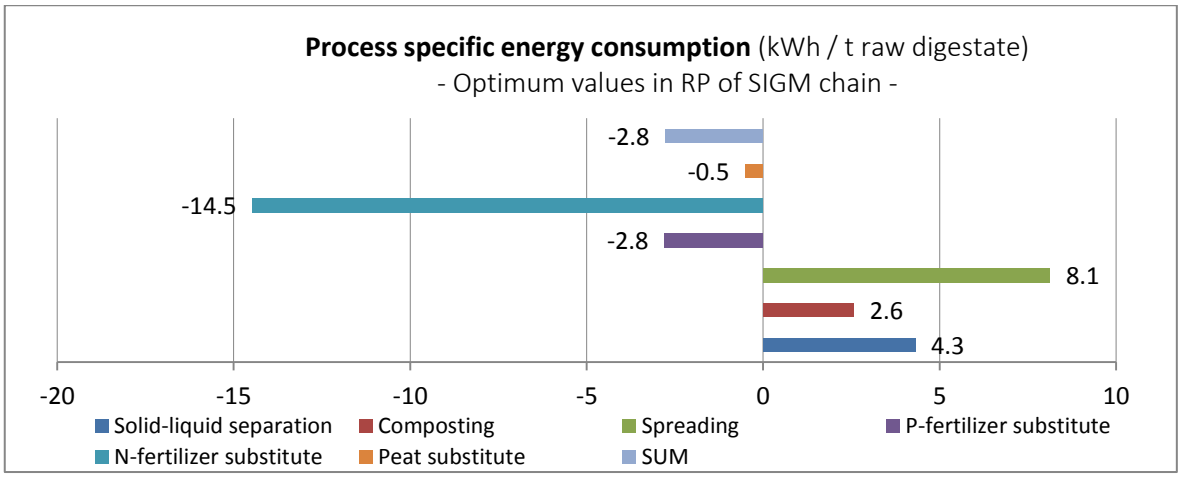

Figure A4.1 Process specific optimal energy consumptions in the reference path (RP) of SIGM chain.

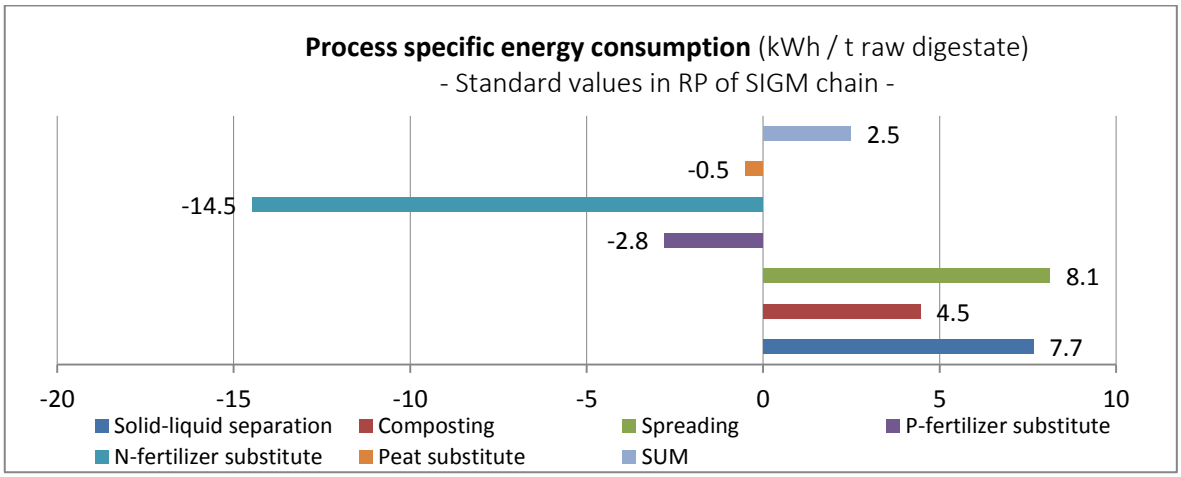

Figure A4.2 Process specific standard energy consumptions in the reference path (RP) of SIGM chain.

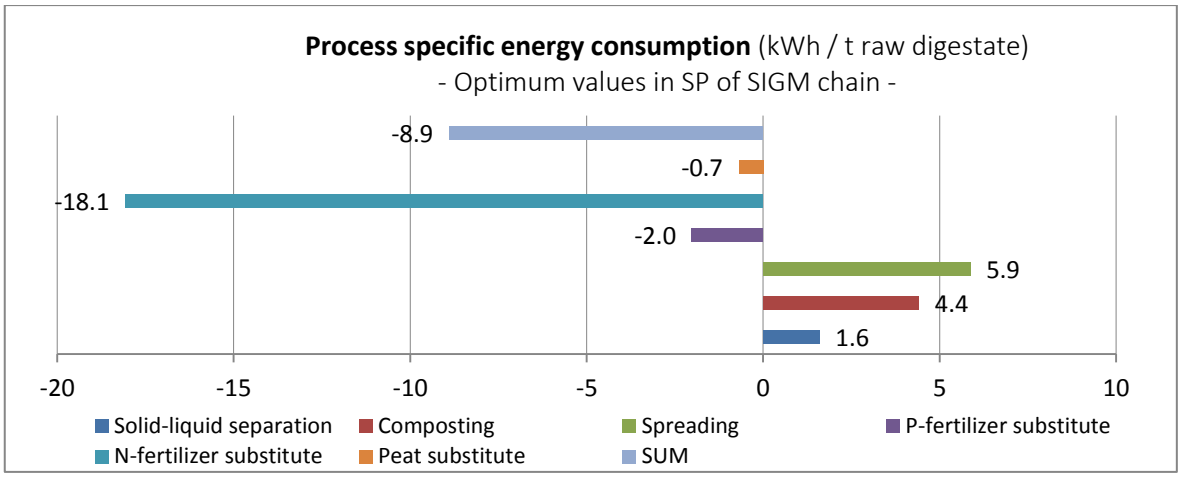

Figure A4.3 Process specific optimal energy consumption with the special option (SP) in SIGM chain.

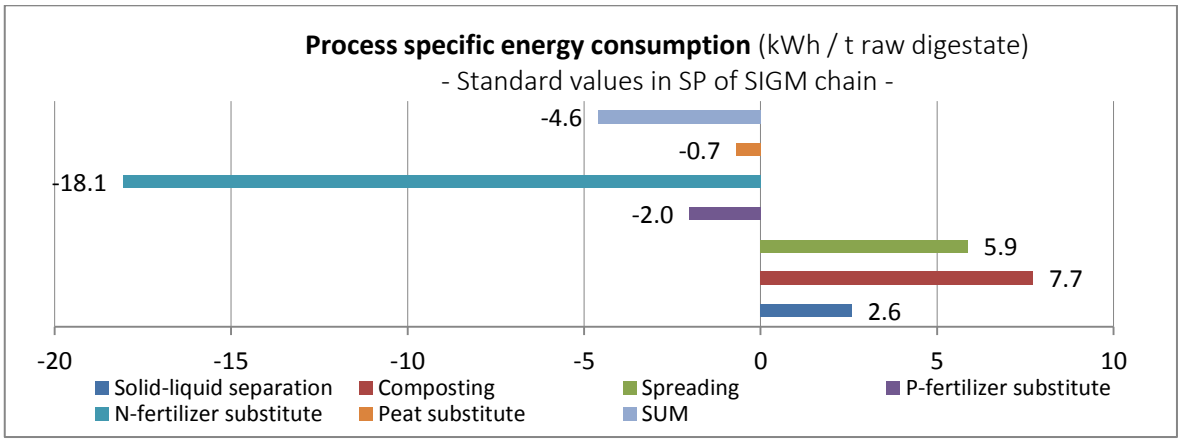

Figure A4.4 Process specific standard energy consumptions with the special option (SP) in SIGM chain.

Solid fuel chain

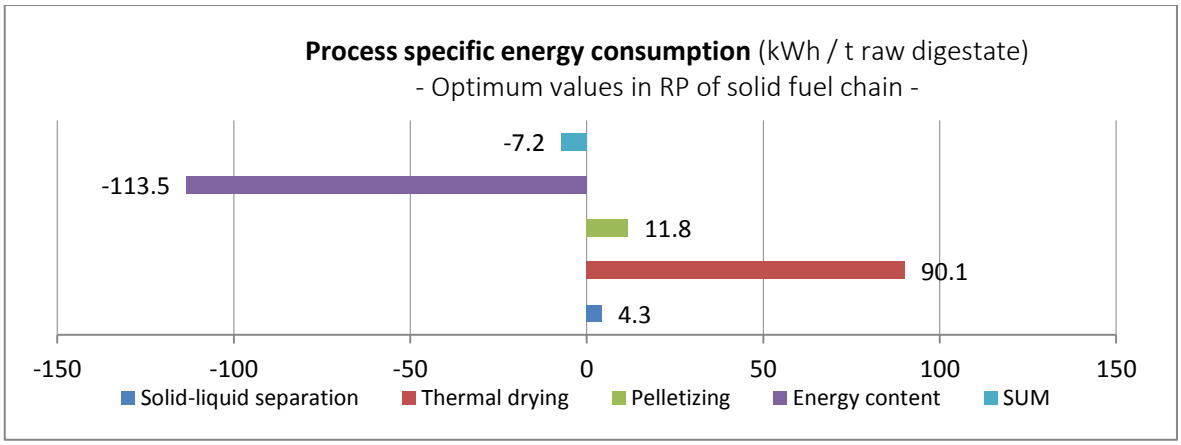

Figure A4.5 Process specific optimal energy consumption in the reference path (RP) of solid fuel chain.

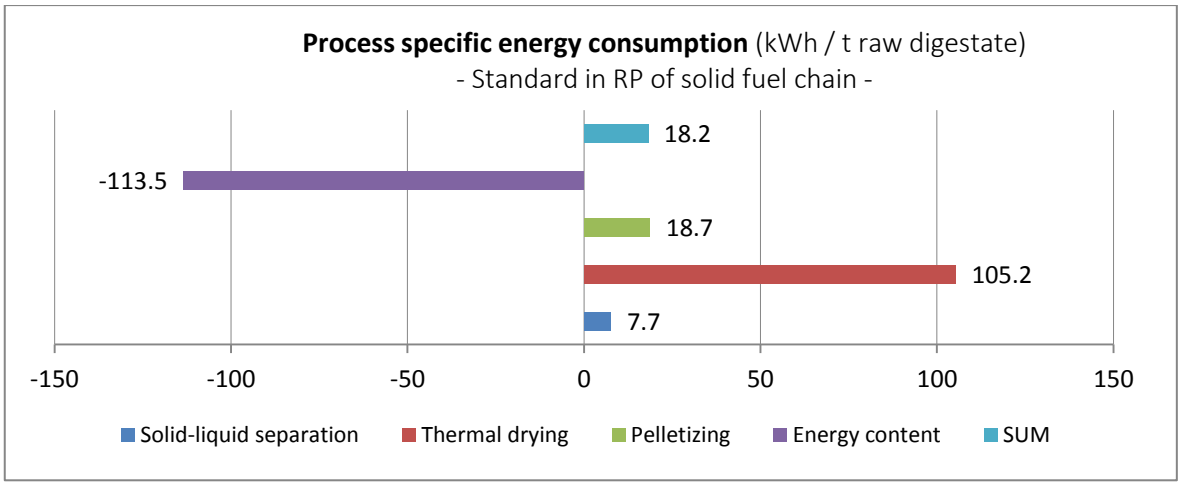

Figure A4.6 Process specific standard energy consumptions in the reference path (RP) of solid fuel chain.

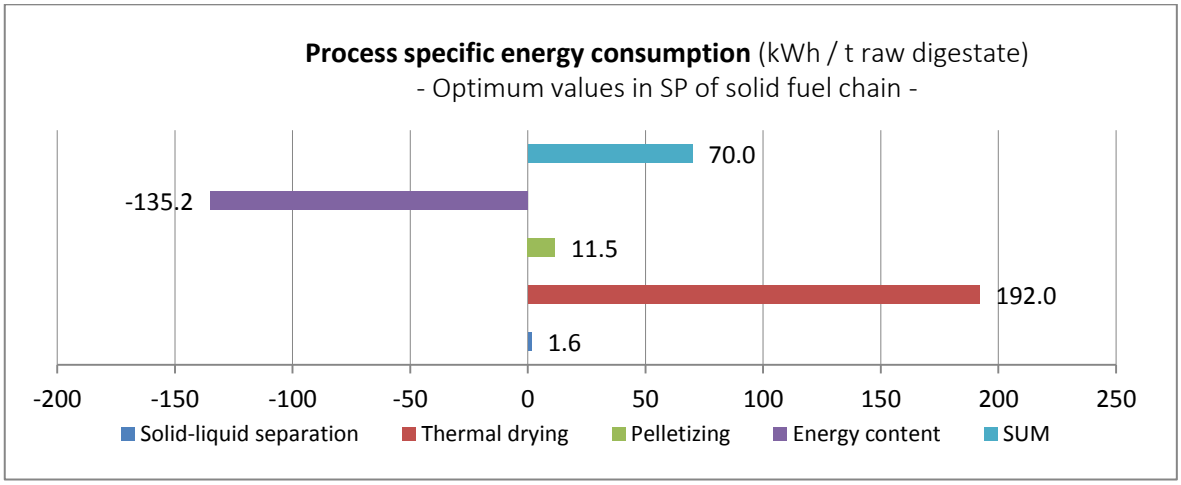

Figure A4.7 Process specific optimal energy consumption with the special option (SP) in solid fuel chain.

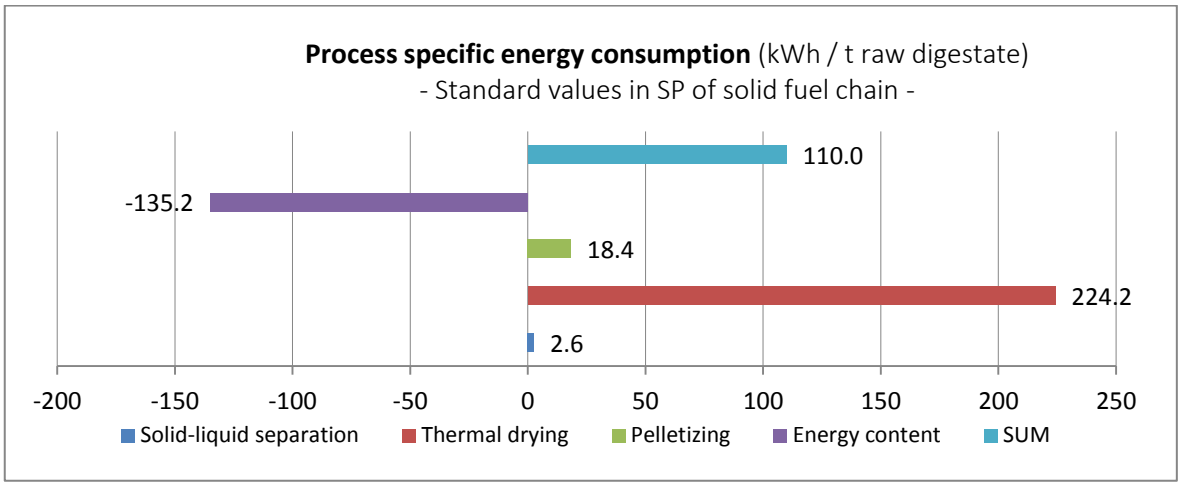

Figure A4.8 Process specific standard energy consumptions with the special option (SP) in solid fuel chain.

Ammonium sulphate fertilizer chain

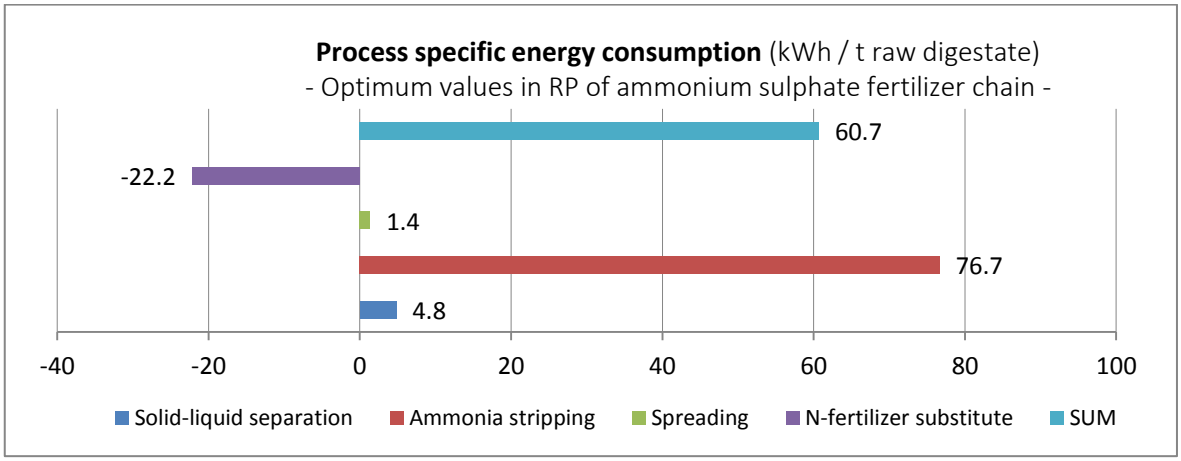

Figure A4.9 Process specific optimal energy consumptions in the reference path (RP) of ammonium sulphate fertilizer chain.

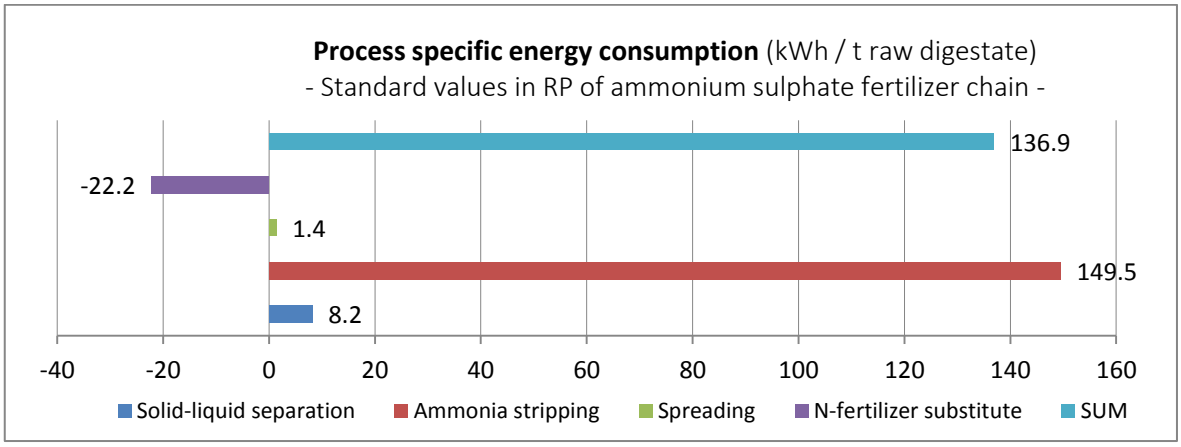

Figure A4.10 Process specific standard energy consumptions in the reference path (RP) of ammonium sulphate fertilizer chain.

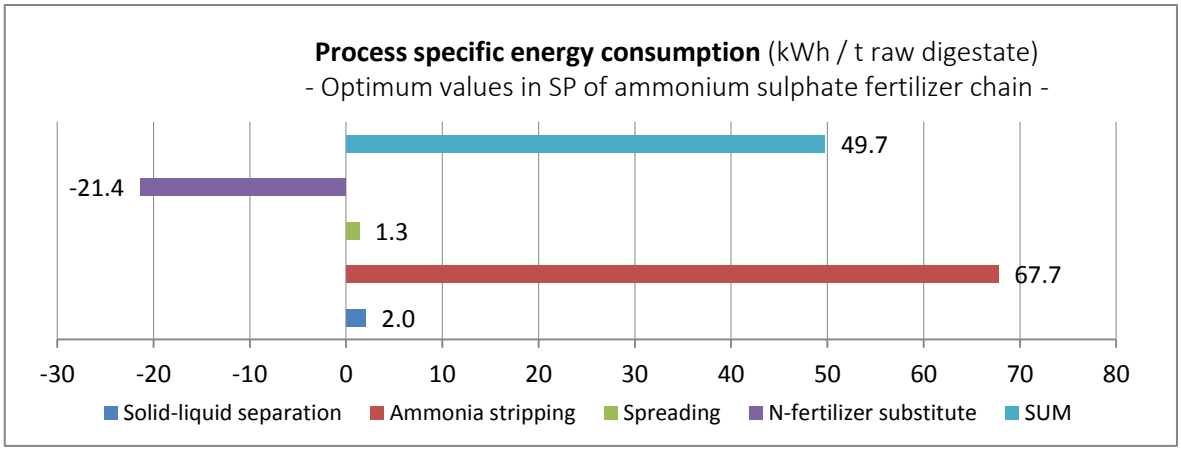

Figure A4.11 Process specific optimal energy consumptions with the special option (SP) in ammonium sulphate fertilizer chain.

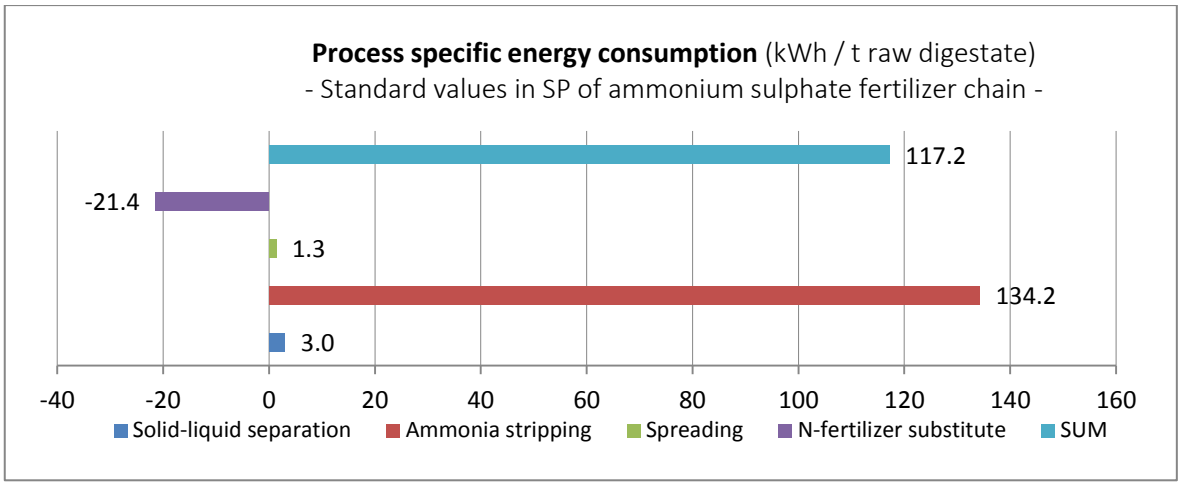

Figure A4.12 Process specific standard energy consumptions with the special option (SP) in ammonium sulphate fertilizer chain.

Liquid fertilizer chain

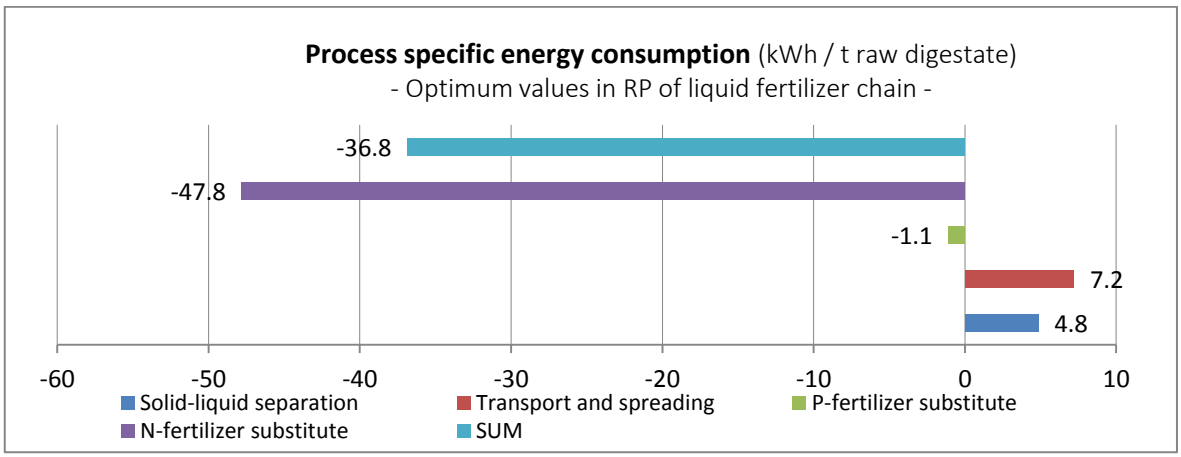

Figure A4.13 Process specific optimal energy consumptions in the reference path (RP) of liquid fertilizer chain.

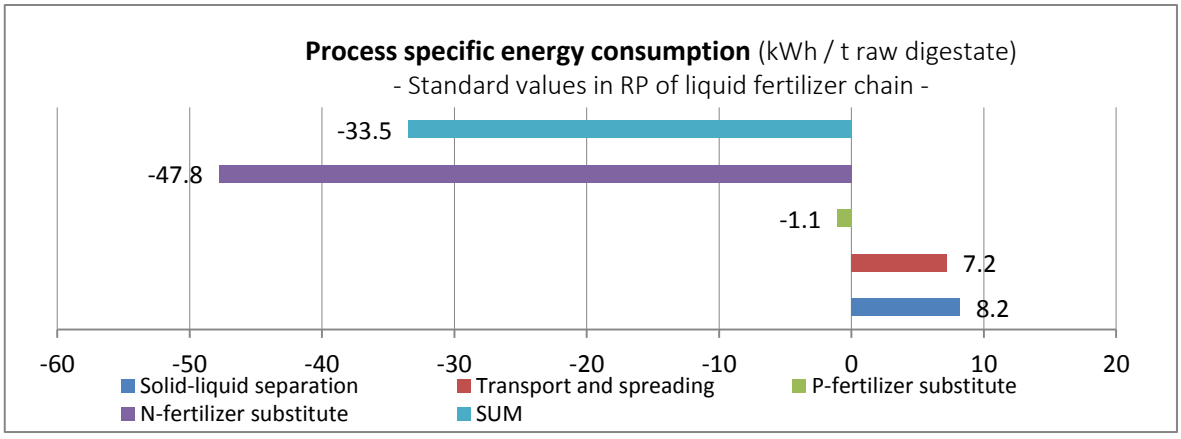

Figure A4.14 Process specific standard energy consumptions in the reference path (RP) of liquid fertilizer chain.

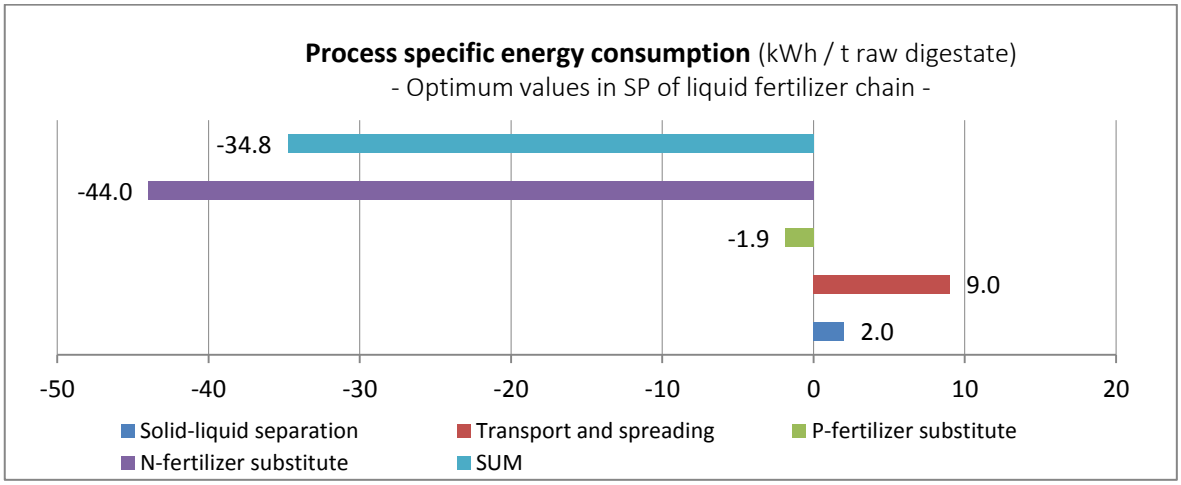

Figure A4.15 Process specific optimal energy consumptions with the special option (SP) in liquid fertilizer chain.

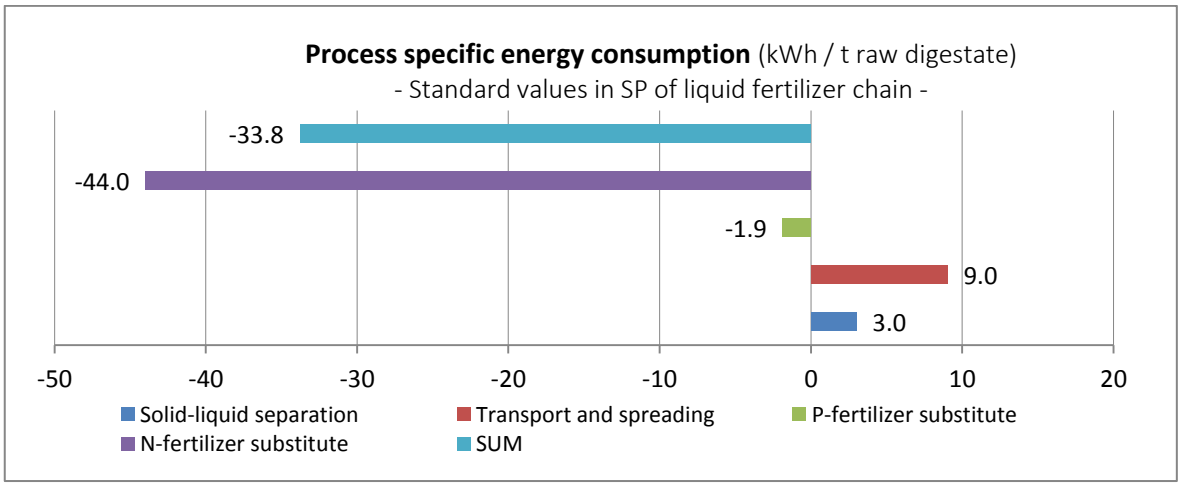

Figure A4.16 Process specific standard energy consumptions with the special option (SP) in liquid fertilizer chain.

Appendix 5: Figures of process specific GHG emissions

Process specific GHG emissions in RPs (reference paths) of each application chain are presented in unit kg CO_2 equivalent per tonne raw digestate in Figures A5.1 – A5.12. The direct emissions of composting, land application and energy production from digestate are considered CO_2-neutral due to the bio-origin. The land applications save emissions from production and use of synthetic fertilizers while the energy content of solid fuel substitutes average energy production emissions in Finland. The processing generates indirect emissions by energy consumption. CO_2 equivalents include direct GWP 100 emissions of CO_2, CH_4, N_2O and SO_2, and indirect NO_x, CO and NMVOC emissions as defined in *the Finnish National Inventory Report under the UNFCCC and the Kyoto Protocol* (Statistics Finland, 2009).

SIGM chain

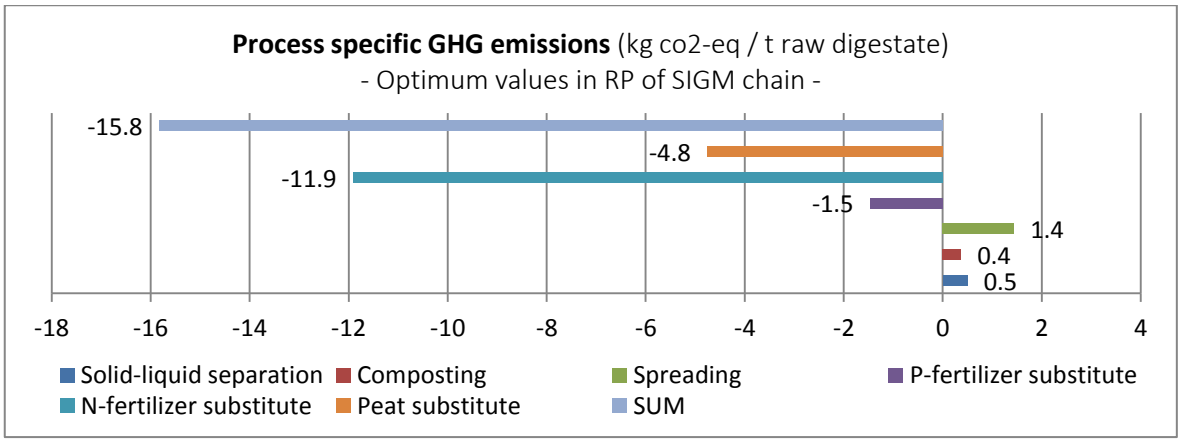

Figure A5.1 Process specific optimum GHG emissions in the reference path (RP) of SIGM chain.

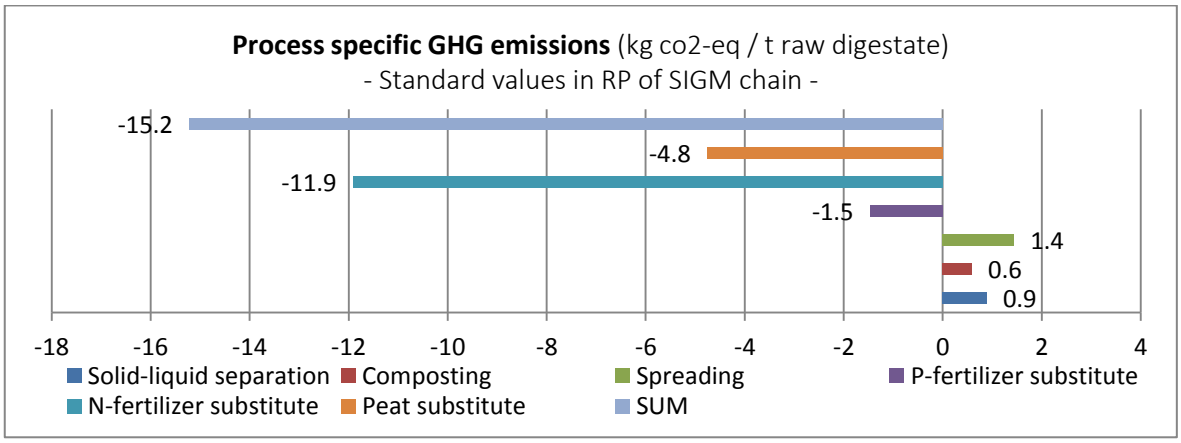

Figure A5.2 Process specific standard GHG emissions in the reference path (RP) of SIGM chain.

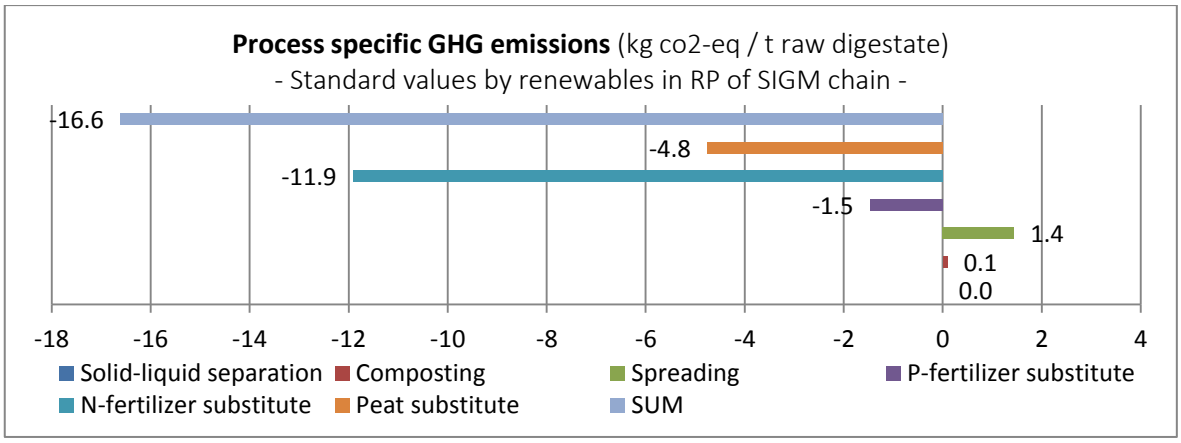

Figure A5.3 Process specific standard GHG emissions in the reference path (RP) of SIGM chain when electricity, heat and primary energy for the processes is produced from renewable energy sources, e.g. biogas.

Solid fuel chain

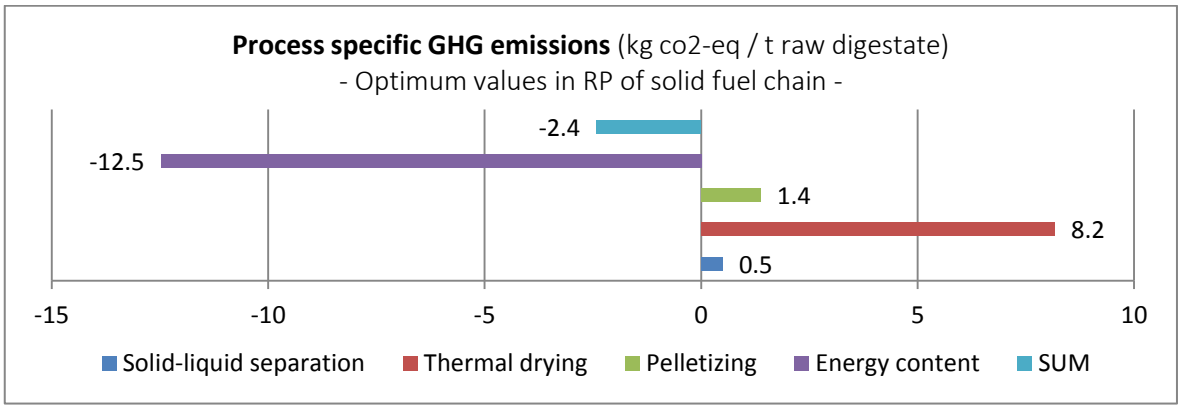

Figure A5.4 Process specific optimum GHG emissions in the reference path (RP) of solid fuel chain.

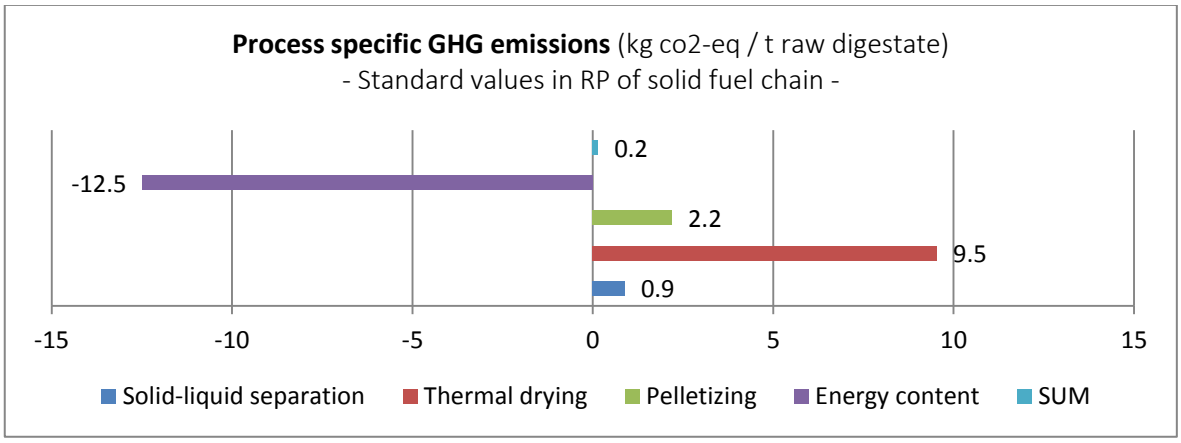

Figure A5.5 Process specific standard GHG emissions in the reference path (RP) of solid fuel chain.

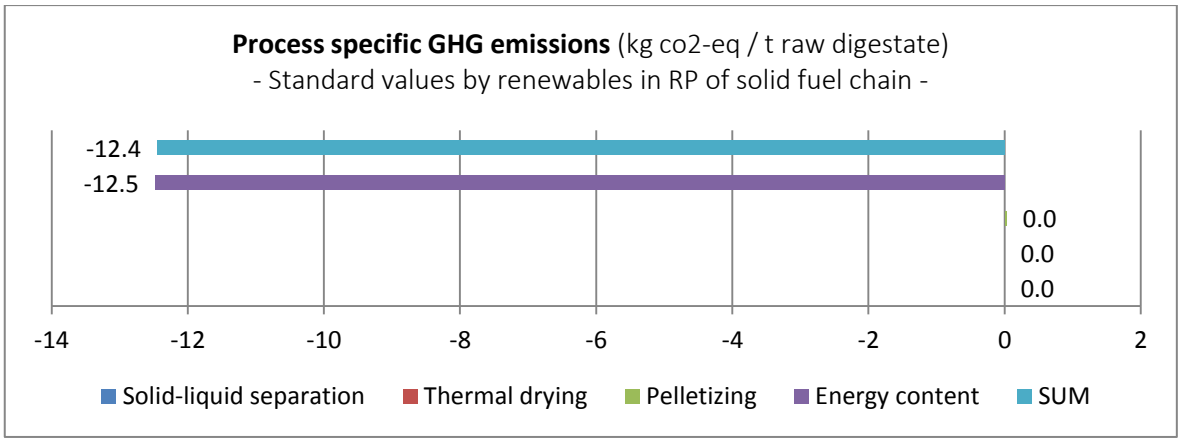

Figure A5.6 Process specific standard GHG emissions in the reference path (RP) of solid fuel chain when electricity, heat and primary energy for the processes is produced from renewable energy sources, e.g. biogas.

Ammonium sulphate fertilizer chain

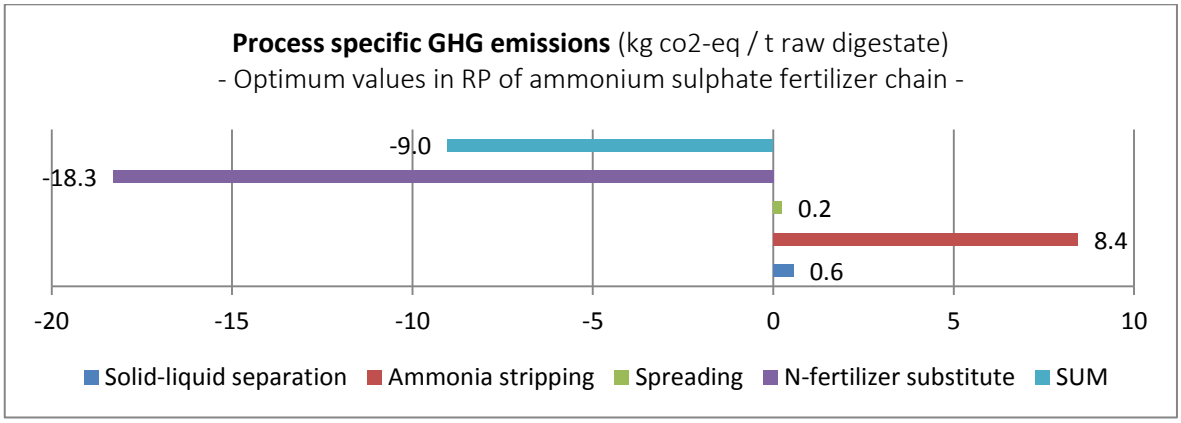

Figure A5.7 Process specific optimum GHG emissions in the reference path (RP) of ammonium sulphate fertilizer chain.

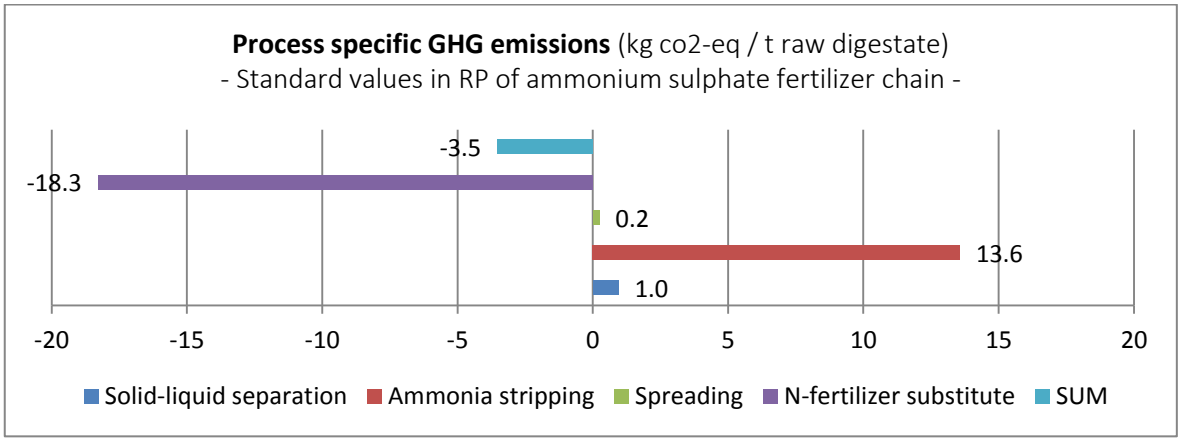

Figure A5.8 Process specific standard GHG emissions in the reference path (RP) of ammonium sulphate fertilizer chain.

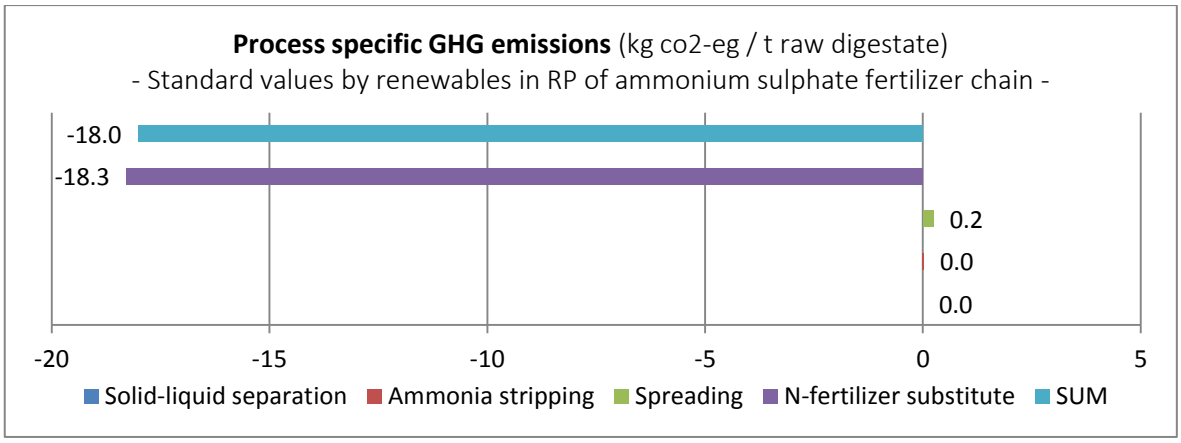

Figure A5.9 Process specific standard GHG emissions in the reference path (RP) of ammonium sulphate fertilizer chain when electricity, heat and primary energy for the processes is produced from renewable energy sources, e.g. biogas.

Liquid fertilizer chain

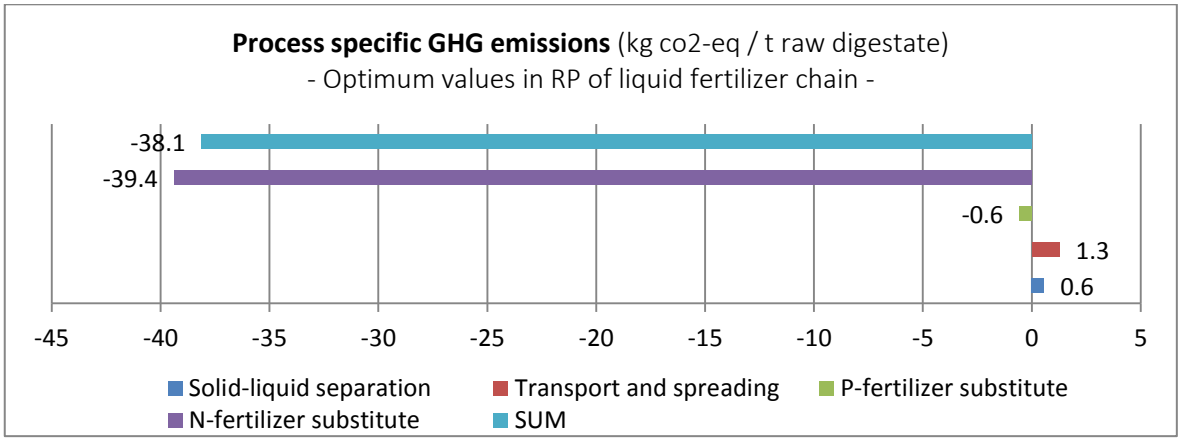

Figure A5.10 Process specific optimum GHG emissions in the reference path (RP) of liquid fertilizer chain.

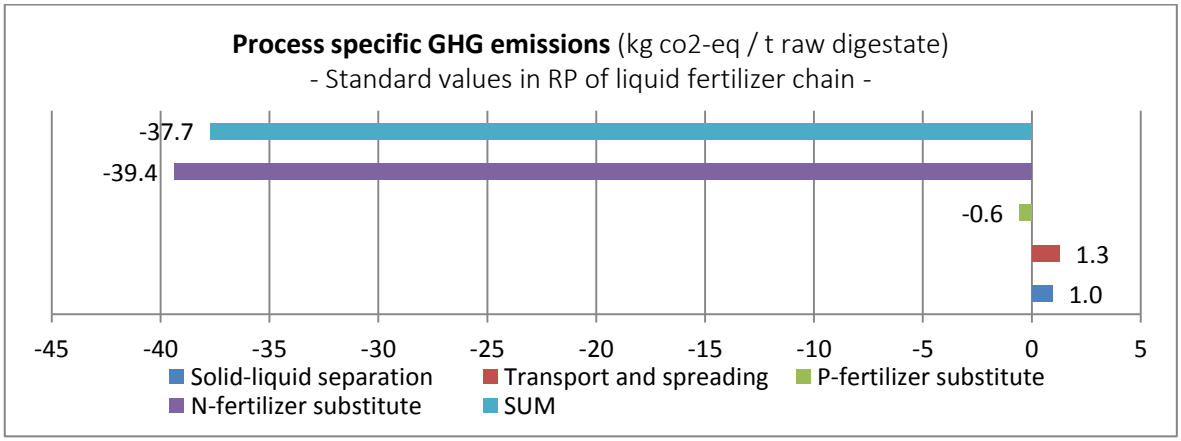

Figure A5.11 Process specific standard GHG emissions in the reference path (RP) of liquid fertilizer chain.

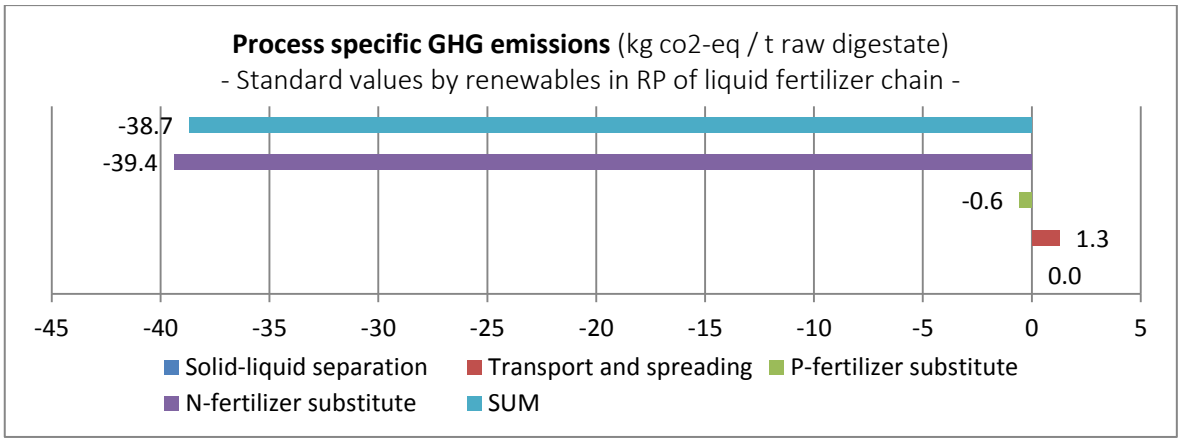

Figure A5.12 Process specific standard GHG emissions in the reference path (RP) of liquid fertilizer chain when electricity, heat and primary energy for the processes is produced from renewable energy sources, e.g. biogas.